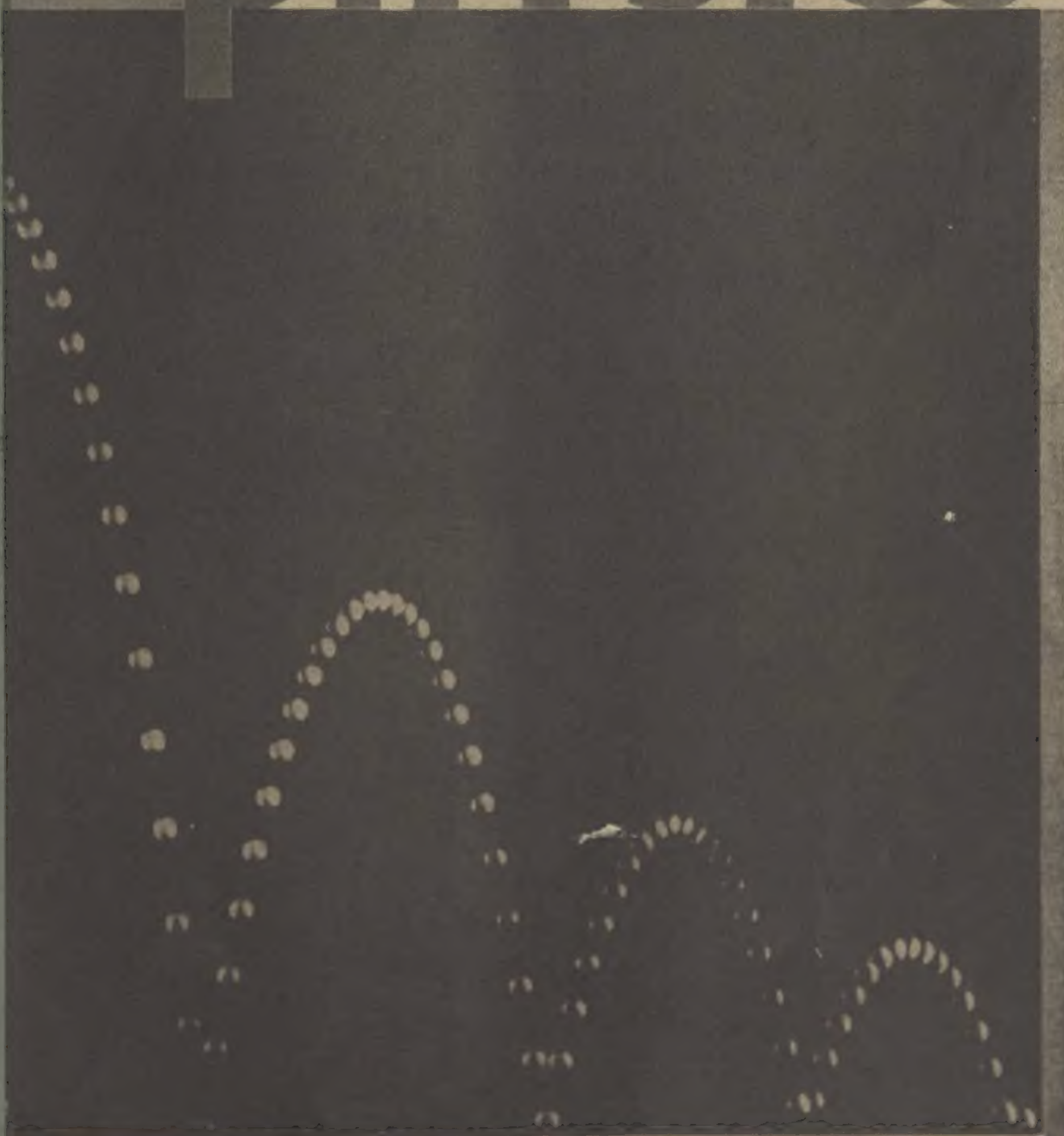
LABORATORY GUIDE

FOR

PHYSICS



INDIAN EDITION

PHYSICAL SCIENCE STUDY COMMITTEE

NATIONAL COUNCIL OF EDUCATIONAL RESEARCH AND TRAINING

PHYSICS

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ACKNOWLEDGMENTS

The ideas for the experiments in this guide come from many sources inside and outside the PSSC. The design of the apparatus, and the drafting and editing of the Guide itself are the fruit of the continued effort of many people. There was a great deal of exchange of ideas and mutual assistance between those working primarily on the text and those working primarily on the laboratory program. It is therefore practically impossible to mention them all here and to describe their individual contributions. Rather extensive acknowledgments will be found at the end of the text. Here I shall necessarily limit myself to a very brief outline of the major developments leading to the present Guide.

Early ideas about the role of laboratory work and ideas for experiments and procedures to make it effective emerged from discussions held in the winter and spring of 1957 by Professors Francis L. Friedman, Elbert P. Little, and Professors Edward M. Purcell, Walter C. Michels, Philip Morrison, and Jerrold R. Zacharias.

Substantial progress on the laboratory front was made at MIT during the summer of 1957 by the groups drafting the text. General questions concerning the place of the laboratory in the course were discussed by a group under the leadership of Professor Zacharias and problems of apparatus were attacked by another group headed by Professor Uno Ingard.

Work on experiments for Parts I and II was continued throughout the year. By the end of the summer of 1958 a preliminary edition of the Laboratory Guide for Parts I and II, edited by Richard Brinckerhoff of Phillips Exeter Academy, was ready for use in the schools.

During the academic year of 1958–1959 the Guide for Parts III and IV was developed, and during the summer of 1959 the Guide for Parts I and II was revised to take advantage of the experience gained in the schools. This job was done primarily by Judson B. Cross of Phillips Exeter Academy, James Henry, and James Strickland of the PSSC staff, Professor Guenter Schwarz of Florida State University, John H. Walters of Browne and Nichols School, and me.

We were greatly assisted in the testing of many experiments by Ervin Hoffart, in the design of apparatus by Nathaniel C. Burwash, and in the production of the Guide by Miss J. Carolyn Safford.

The line drawings were done by Percy Lund and the photographs were taken by Miss Berenice Abbott and Dr. Strickland.

In directing the efforts of the laboratory group, I benefited from many suggestions made by Professor Friedman, who kept a watchful eye over our progress.

The present edition differs only in minor parts from that preceding it. Most of the changes are due to improvement in apparatus. Richard T. Wareham of D. C. Heath contributed a great deal to the neat and practical form of this guide.

Uri Haber-Schaim

PREFACE

Physics describes the world around us. We look for relations between the various facets of the observed behavior of nature. To understand this basic job of physics, the laboratory is a primary source of learning. Indeed, ideas, concepts, and definitions make real sense only when they are related to experience.

To provide this experience, a laboratory program was developed as an integral part of the Physical Science Study Committee course in physics. This program is designed to give students first-hand familiarity with physical realities. It enables them to wrestle with the main laws of physics for themselves, largely at their own pace.

The laboratory work is embodied in this Guide and the accompanying apparatus with which the experiments can be carried out., (Additional information and suggestions are included in the Teacher's Guide.) Most of the experiments in this guide are so presented as to pave the way for reading the text. Thus, students can investigate physical phenomena rather than just verifying known conclusions. When a student performs experiments, the results of which are not known to him in advance, he gains a feeling of personal participation in the discoveries of science; both science and the role of the scientist become more meaningful to him. For this reason, detailed instructions have been limited to purely technical aspects of the experiments; and the necessary guidance on the physical ideas is supplied in short introductions and by asking leading questions.

Students need not end an experiment at any definite point. Usually there is a first basic part of the experiment which all students can complete. Other students, proceeding at their own pace, will go to the more advanced questions which are raised toward the end of the description of each experiment. This procedure allows both the teacher and the student a considerable amount of choice, although there is enough direction so that important ideas are sure to be emphasized. Furthermore, this procedure stimulates an appreciable number of students to go into interesting, related investigations on their own.

The equipment provided to carry out this program is very simple. There are two reasons for this, one pedagogical and one financial. Complicated apparatus is apt to obscure the basic simplicity of the subject under investigation, while simple apparatus makes it easy both to see the principles of physics and to appreciate how these principles influence the design of measuring instruments. In addition, because the apparatus is made of common materials, it can be duplicated and used at home. Thus the laboratory helps to prevent a split between the student's world and that of science. (In fact these two worlds are the same, and when they appear to be separated, science has become a rigid doctrine instead of a continuing study of the world.)

The Laboratory Guide, like the text, is divided into four parts. The first part mainly concerns such questions as—"How long does it take?" "How big or small is it?" "How fast does it move?" Parts II to IV deal with the basic laws and concepts of optics, dynamics, electricity, and atomic physics. There, typical questions are—"How is light refracted?" "How does the acceleration depend on the force?" "What is the mass of an electron?"

During the course of laboratory work students learn that experiments are generated as a result of ideas, that experiments are designed so that their results can be interpreted, and that they are incomplete unless they are analyzed.

This laboratory program, like the other parts of the PSSC course, has been tried out by hundreds of teachers and many thousands of students. Their experience shows that the program can be highly successful. The experiments indeed give depth and meaning to the text, and in return, the text, in helping to interpret the experiments, leads back into the laboratory. Thus, the interplay of theory and experiment, so characteristic of the development of science, is carried on in a way that students can grasp.

TO STUDENTS

This Guide is designed to help you with your laboratory work. It provides a general introduction to the problems at hand, gives you technical hints, but leaves the thinking to you. You will be on your own a great deal. If you are like the many others who have used these experiments, as you work through them, you will soon learn to enjoy this kind of laboratory work.

Throughout this Guide you will find many questions. Finding the answer to these questions may sometimes require a little thought about what you have done before, or it may require a short calculation. Sometimes more experimentation will be called for. It is up to you to decide what to do in each case.

Good working habits are useful. Always read the whole description of an experiment before you begin to work so you will have a clear understanding of what you are trying to do. Keep a clear record of your experiment as you perform it. Then you will have the data to refer to when needed, and sufficient information to know what you did.

In the course of an experiment, whenever necessary, repeat your measurements a few times. Several readings are usually better than one.- You should decide when more measurements are needed.

Many of these experiments require the help of one or more partners. Discuss results with your partners. You may learn more by working together on an analysis than by going at it alone.

You will probably not find it possible to do all the parts of every experiment. Do not rush; you will get more out of doing half the things suggested in an experiment thoroughly than all of them superficially. Often, part of the analysis may be done at home.

The apparatus used in most experiments is quite simple. You can make many items yourself and experiment further at home.

CONTENTS

LABORATORY GUIDE

PART I

I-1. *SHORT TIME INTERVALS*

Everybody knows how to measure the time it takes an athlete to run 100 yards. If reasonable accuracy is sufficient, an ordinary wrist watch with a second hand will do. But, can you measure the time it takes the vibrating clapper of an electric bell to make one complete vibration? Connect a battery to a bell for a few seconds and try! (Fig. 1.) You will find the time of one vibration so short that it is impossible to measure it with only a watch. In this experiment you will learn a method of measuring such short times.

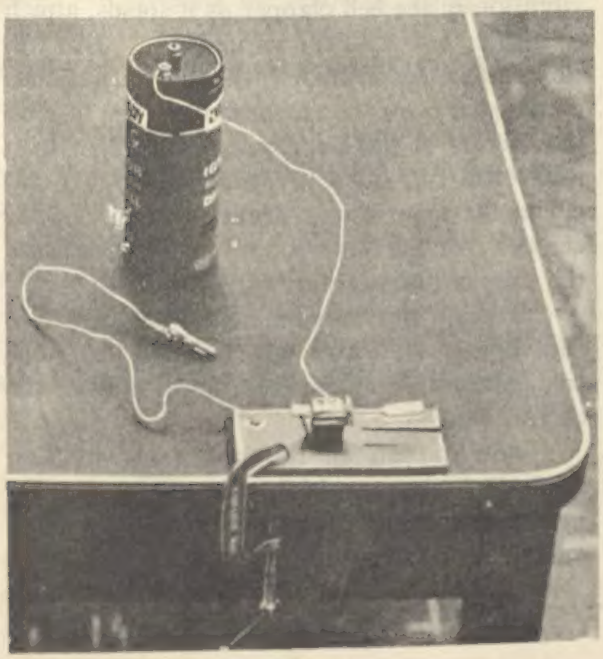


Figure 1

Let us start with a larger "clapper," a loaded strip of steel, which does not vibrate so rapidly (Fig. 2). Pull the clamp sidewise and release it. With your wrist watch, can you measure the time it takes the blade to complete one vibration?

Unlike the motion of the athlete, the motion of the blade repeats itself regularly. You can make use of this repetition by measuring the time it takes to complete, say, 10 vibrations. Will this increase the accuracy of your measurement?

You can easily count the vibrations of the blade, but you need a way of counting faster to

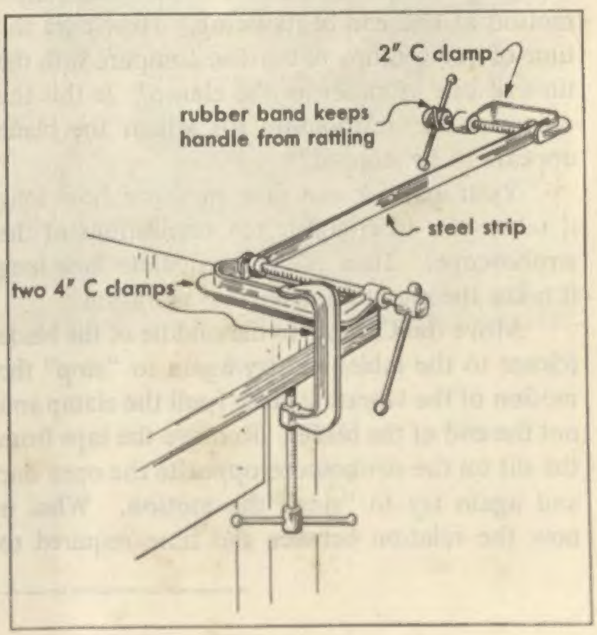


Figure 2

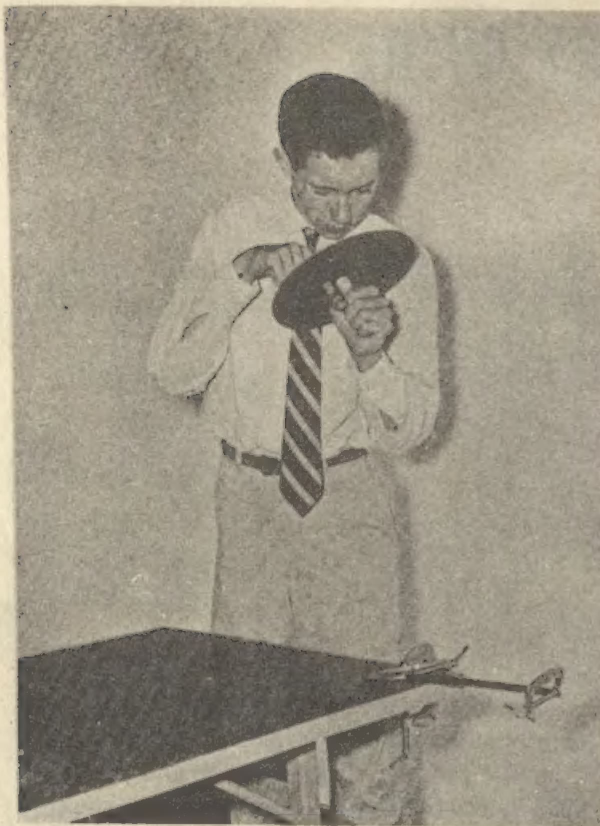


Figure 3

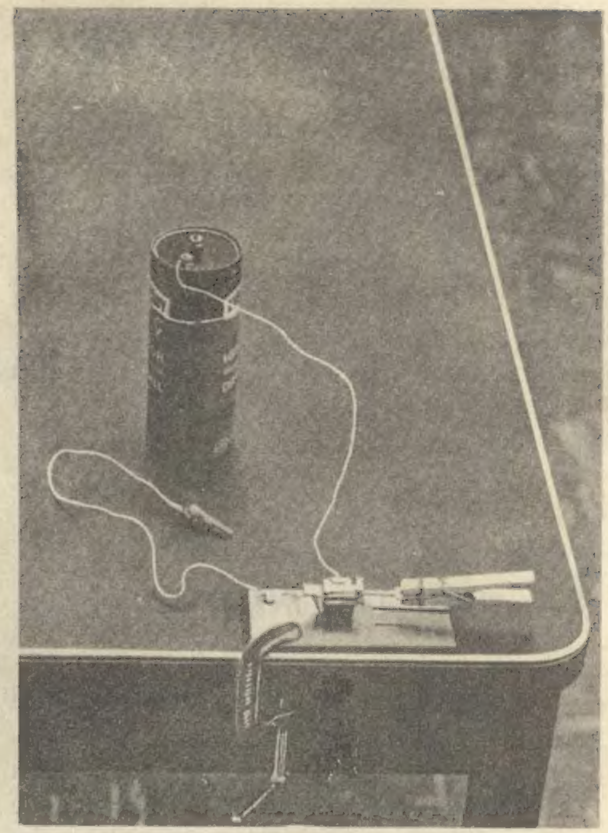


Figure 4

be able to count the vibrations of the clapper. One way of doing this utilizes a disc stroboscope (Fig. 3). First cover all the stroboscope slits, except one, with tape. While looking at the vibrating clamp, rotate the stroboscope slowly in front of your eye as shown in Fig. 3. By changing the rate of rotation, "stop" the clamp's motion at one end of its swing. How does the time of one rotation of the disc compare with the time of one vibration of the clamp? Is this the only possible relationship for which the blade appears to be stopped?

Your partner can now measure how long it takes you to complete ten revolutions of the stroboscope. Then you can calculate how long it takes the clamp to make one vibration.

Move the C clamp to the middle of the blade (closer to the table) and try again to "stop" the motion of the vibrating blade (pull the clamp and not the end of the blade). Remove the tape from the slit on the stroboscope opposite the open one and again try to "stop" the motion. What is now the relation between the time required to complete one revolution of the stroboscope and one vibration of the clamp? How long does one vibration take? What is the time of one complete vibration when the C clamp is moved still closer to the table?

Before you try to measure the time of one vibration of the bell clapper as it stands, attach a clothespin to it as shown in Fig. 4. This will slow the clapper down and will give you a chance to practice using the stroboscope. Try to stop the motion of the clapper and clothespin with four open slits on your stroboscope. To calculate the time of one vibration of the loaded clapper, you may find it convenient to measure the time of twenty rotations of the disc.

Repeat your measurement with all twelve slits open. How can you be sure that your calculations in both cases do not give twice the correct value?

Now you can find the time of one vibration of the bell clapper without the clothespin. By how many orders of magnitude have you extended your ability to measure short times?

By finding the time of one vibration of the clapper, you have calibrated the bell and can now use it to measure short time intervals.

You can use this apparatus as a recording timer to measure the time interval between two handclaps (Fig. 5). When the paper tape is pulled through, the clapper will leave marks at equally spaced time intervals. Try several practice runs to make sure that the clapper is marking the paper tape and to determine how fast to pull the paper tape to have the marks adequately spaced for counting. While you are pulling the paper tape through the timer, have your partner clap twice. Turn on the timer at the sound of the first clap and turn it off at the second clap. Count the number of marks on the paper tape and determine the time interval between claps.

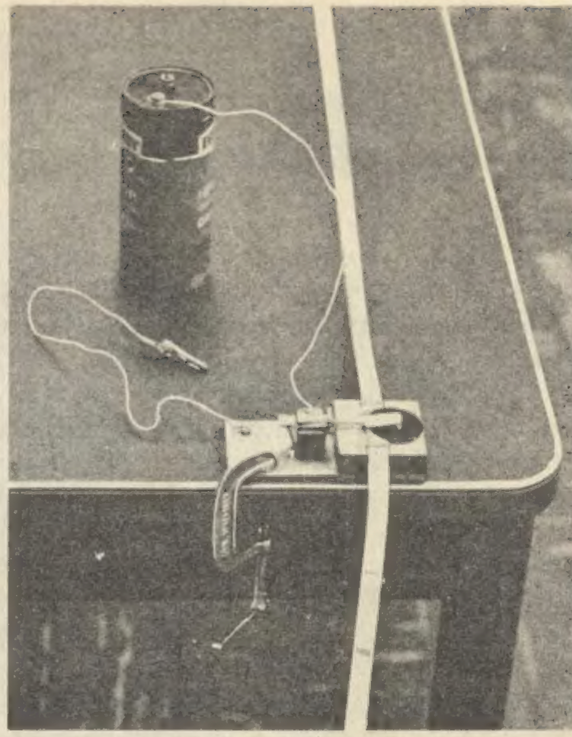


Figure 5

We cannot "stop" a nonrepetitive motion by viewing it through a stroboscope. However, by counting how many times we see the moving object while it moves from one place to another, we can find how long it takes to move this distance. To facilitate the counting, we can make a permanent record of the motion by photographing it through a stroboscope (Fig. 6) or by using the timer.

Tie the tape to a small object and measure the time it takes the object to fall from the table to the floor.

How could you use the tape and a watch to calibrate the bell timer?

Compare the time of one vibration measured when the clapper vibrates freely with the time of one vibration when the clapper hits the tape.

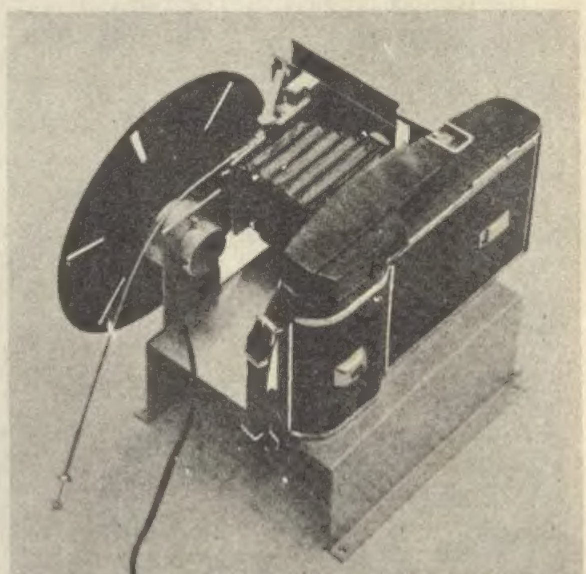


Figure 6

I–2. LARGE DISTANCES

Distances of the order of a meter are easily measured directly with a ruler. For much larger distances the use of a ruler becomes impractical, and in some cases impossible.

Various instruments can extend our ability to measure larger distances. You can calibrate them experimentally and use them successfully without understanding how they work. A mathematical calibration, on the other hand, requires such an understanding. In this experiment you will learn to use two simple instruments; you will calibrate one experimentally and one mathematically.

The Range Finder

To see how the range finder (Fig. 1) operates, look at a lamp post or a tree a few meters distant in the following way: first look at the post over the fixed mirror and then rotate the range finder until you see the movable mirror in the fixed one. Finally adjust the arm so you see the image of the post in the movable mirror in line with the post itself. Mark the position of the pointer on the paper. Now sight the same object from a different distance and notice the change in position of the pointer.

Calibrate your range finder by sighting objects placed at known distances and marking the pointer's positions on the paper.

Find the distance of several objects. How does the accuracy of the range finder change with distance? At what distance is the error about 100%?

Figure 1

Figure 2

The Parallax Viewer

To measure a distance of the order of a kilometer we like to have an instrument simple enough to be calibrated mathematically. The parallax viewer shown in Fig. 2 is such an instrument.

To understand what we mean by parallax, look at a pencil with one eye at a time and notice its apparent shift with respect to the background. This shift is called parallax. To see it on a larger scale, sight two objects which form a straight line with you and are at greatly different distances. Move a few steps at right angles to your line of sight and look again. Notice that the two objects are no longer in line with you. We shall use this shift to find the distance to the nearer of the two objects; the farther one will serve only as a reference point in the background.

To determine the shift quantitatively go back to the place where the two objects were in line (*B* on Fig. 3). From that point measure a base line *BC* perpendicular to the sight line. At *C* use the parallax viewer and sight the reference point over the paperclip. Then mark the line of sight to the nearer object by adjusting the pointer on the crossarm. From the position of the pointer on the crossarm and the distance between the two sighting positions (the base line) you can find the desired distance.

(Turn the page.)

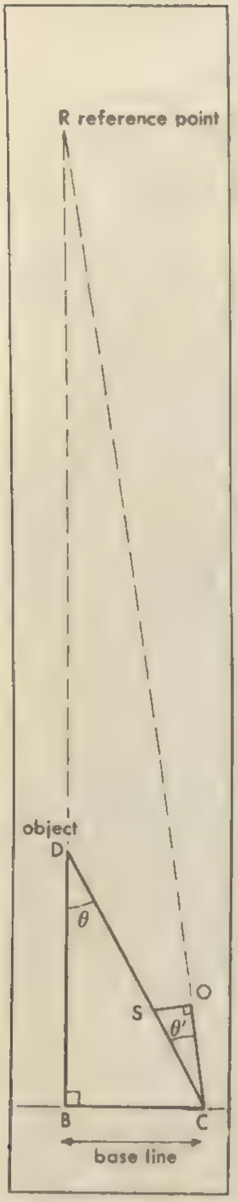


Figure 3. The size of the viewer as indicated by the lengths CO and OS is vastly exaggerated in comparison with the distances BC and BD.

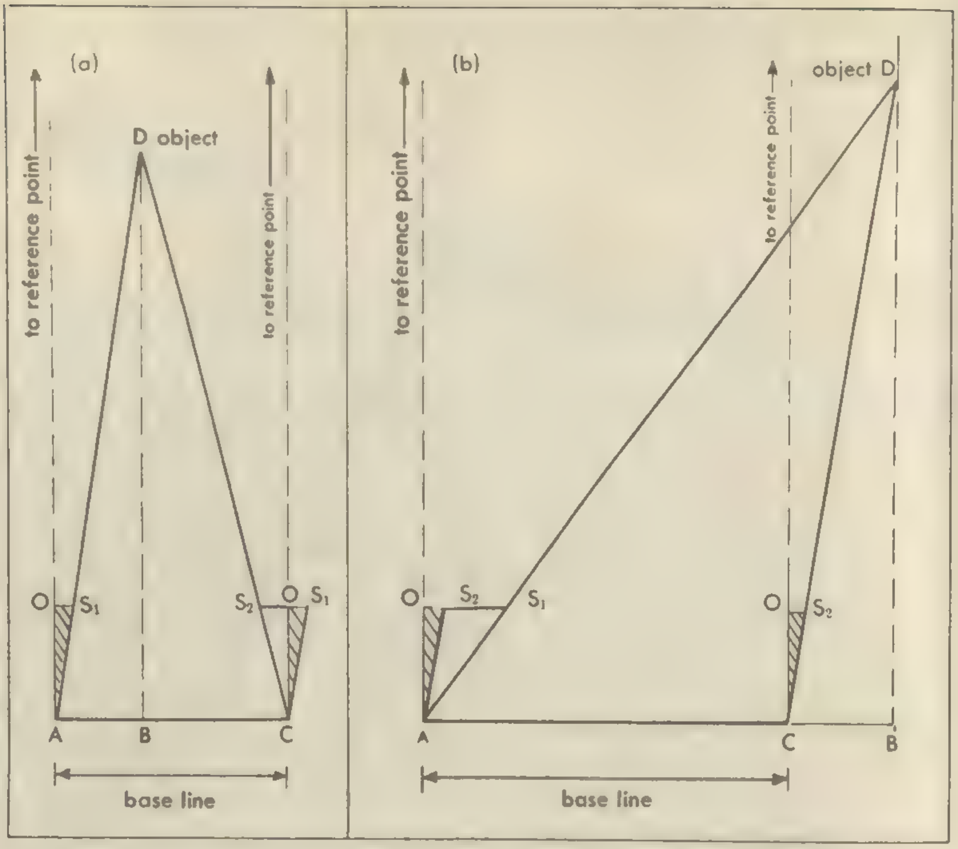


Figure 4

On the schematic drawing of the situation, shown in Fig. 3, note that the angles θ and θ' are not very different. If the reference point has been chosen very far away compared to the distance to be measured, θ practically equals θ' and the triangles *BDC* and *OCS* are similar. How can you express the distance *BD* in terms of the length of the base line *BC*, the distance between the scale and the pinhole *CO*, and the parallax reading of the pointer on the scale *OS*?

In practice, it is not necessary that the distant reference point be initially in line with the object. You can sight the reference point as before and mark the line of sight to the object with one pointer (S_1 in Fig. 4a). Then move at right angles to the direction of the point of reference, sight again, and mark the direction of the object with a second pointer (S_2 in Fig. 4a). From the similar triangles *ADC* and S_1CS_2 you can calculate the distance *AD*.

Notice that the base line and the perpendicular from the object to it need not intersect (Fig. 4b).

Measure several distances to objects in the kilometer range, using different reference points. Which of these measurements do you consider most accurate?

I–3. *SMALL DISTANCES*

You can measure the thickness of a piece of cardboard with a ruler. For much smaller lengths, the readings from the ruler become very inaccurate. Using a ruler to measure the thickness of a hair will only show that a hair is very thin, something you knew before you started. The optical micrometer (Fig. 1) permits considerable extension of your ability to measure very short distances.

To see how sensitive it is, hold your micrometer so you can see the image of the reference pin in the mirror. (The pin should be near the right end of the arm.) While looking through the "V" in the sight, move the sight to the right or left until the pin's image, as seen through the "V," is in line with the right edge of the ears on the mirror block. Mark the position of the sight. Insert a single piece of paper between the mirror

Figure 1

and the inner glass plate (Fig. 2) and find the new direction in which you see the image of the pin in line with the sight and the right edge of the ears. Mark this position. How does the distance between the two marks compare with the thickness of the paper?

The optical micrometer can be calibrated mathematically, but this is rather complicated. It is much simpler to calibrate the micrometer experimentally. To do this, you may use thin objects of known thickness, such as wires of specified diameters, which can be inserted between the mirror and the glass plates.

You can also calibrate the micrometer with objects whose thickness you can calculate. For example, with a ruler you can measure the thickness of a writing pad, count the number of pages and calculate the thickness of each. Then to calibrate the micrometer insert pieces of paper, one by one, and mark the position of the sight on the scale. Repeat each step to see whether your marks fall on the same place, thus getting an idea of the accuracy of your calibration. Use your micrometer to find the thickness of a hair, a piece of aluminum foil or cellophane.

Press two razor blades together and make two sharp cuts on a piece of paper. How could you use the optical micrometer to determine the distance between the two cuts? What assumptions have you made?

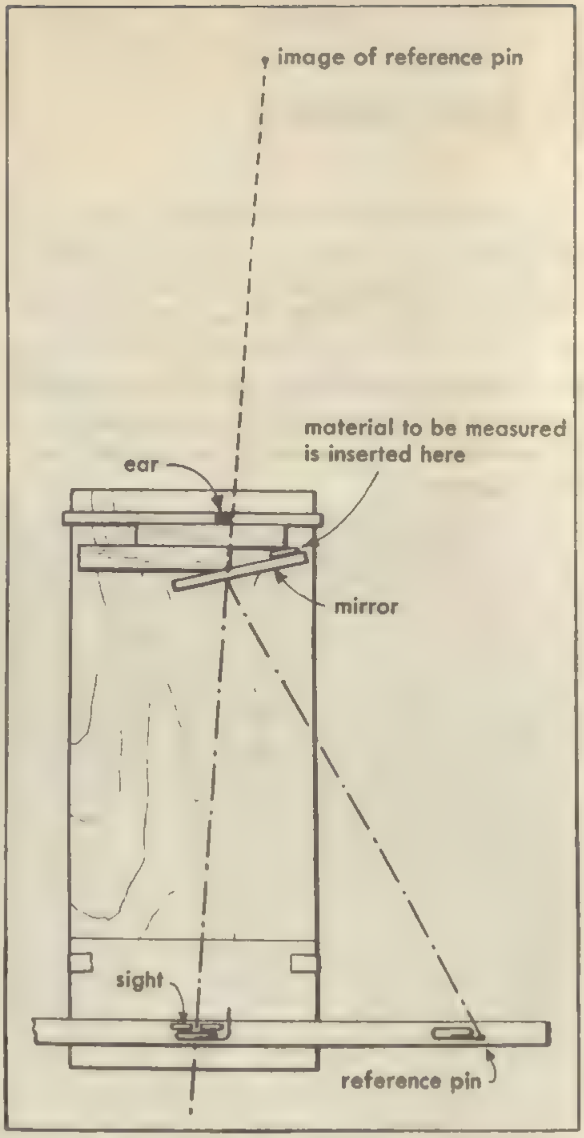


Figure 2

I-4. *ANALYSIS OF AN EXPERIMENT*

In Table 1 are the results of an experiment. You are asked to present and analyze these results in a form which will enable you to draw conclusions about the nature of the process under investigation and to predict the outcome of similar experiments. The presentation and analysis of experimental results is an essential part of physics.

The experiment was an investigation of the time it takes water to pour out of a can through a hole in the bottom. As you would expect, this time depends on the size of the hole and the amount of water in the can.

To find the dependence on the size of the hole, four large cylindrical containers of water of the same size were emptied through relatively small circular openings of different diameters. To find the dependence on the amount of water, the same containers were filled to different heights.

Each measurement was repeated several times and the averages of the times (in seconds) that each container took to empty have been entered in the table. Because of the difficulty of measuring short times accurately with a watch, there are fewer significant figures in the measurement of short times than in those of the longer times.

Table 1

Times to Empty (secs)

d in cm \ h in cm	30	10	4	1
1.5	73.0	43.5	26.7	13.5
2	41.2	23.7	15.0	7.2
3	18.4	10.5	6.8	3.7
5	6.8	3.9	2.2	1.5

All the information we shall use is in the table, but a graphical presentation will enable us to make predictions and will greatly facilitate the discovery of mathematical relationships.

First, plot the time versus the diameter of the opening for a constant height, say that of 30 cm. It is customary to mark the independent variable (in this case, the diameter d) on the horizontal axis and the dependent variable (here the time t) on the vertical axis. To get maximum accuracy on your plot, you will wish the curve to extend across the whole sheet of paper. Choose your scales on the two axes accordingly without making them awkward to read.

Connect the points by a smooth curve. Is there just one way of doing this? From your curve, how accurately can you predict the time it would take to empty the same container if the diameter of the opening was 4 cm; 8 cm?

Although you can use the curve to interpolate between your measurements and roughly extrapolate beyond them, you have not yet found an algebraic expression for the relationship between t and d. From your graph you can see that t decreases rather rapidly with d; this suggests some inverse relationship. Furthermore, you may argue that the time of flow should be simply related to the area of the opening since, the larger the area of the opening, the more water will flow through it in the same time. This suggests trying a plot of t versus $1/d^2$.

To do this, add a column for the values of $1/d^2$ in your notebook and, again choosing a convenient scale, plot t versus $1/d^2$ and connect the points with a smooth curve. What do you find? Was your conjecture correct? Can you write down the algebraic relation between t and d for the particular height of water used?

To find whether this kind of relationship between t and d also holds when the container is filled to different heights, on the same sheet of graph paper, plot the graphs of t versus $1/d^2$ for the other heights. What do you conclude?

Notice that the graph for $h = 1$ cm extends upward very slightly. Make a special plot of these data on a larger time scale so you will use the whole sheet. What do you observe? On the basis of your data, what can you say about the algebraic relation between t and d for $h = 1$ cm?

Now investigate the dependence of t on h when the diameter of the opening stays fixed. Take the case of $d = 1.5$ cm which is the first row. Make a plot in which h will be marked on the horizontal axis and connect your points by a curve. Extrapolate the curve toward the origin. Does it pass through it? Would you expect it to do so?

How can you use your plots of t versus $1/d^2$ to predict t for $h = 20$ cm and $d = 4$ cm?

There is no simple geometric consideration to guide us to the right mathematical relation between t and h. You can try to guess it from the curve. It may be helpful to rotate the graph paper through 90° and look first at h as a function of t, and then at t as a function of h. If you succeed, check by proper graphing to see if the same kind of relation between t and h holds for $d = 5$ cm.

If you are familiar with logarithms, you can check to see if the relation belongs to a general class of relations, such as a power law, $t \propto h^n$. To do this, plot log t versus log h (or simply t versus h on log-log paper). What do you obtain? What is the value of n?

Can you find the general expression for time of flow as a function of both h and d? Calculate t for $h = 20$ cm and $d = 4$ cm and compare the answer with that found graphically. Which do you think is more reliable?

I–5. MOTION: SPEED AND ACCELERATION

Studying the motion of an object requires a record of the object's position at different times, preferably at regularly spaced time intervals. With such a record, you can study quite irregular motion—for example, the motion of your hand while you walk.

Set up the timer as shown in Fig. 1, grasp the end of the tape in your hand and walk several steps while your partner operates the timer.

From an inspection of your tape, can you find where your speed was highest? Where it was lowest? Can you find where the acceleration was (a) greatest, (b) smallest? If you choose the time interval between two consecutive marks as a unit of time, a "tick," what does the distance between any two adjacent marks represent?

Find the speed during each interval of five "ticks." Plot the speed as a function of time, taking five ticks as your unit of time. Was the speed constant? If not, by what per cent did it vary from the average speed over the whole trip?

From this graph, plot the distance traveled versus time by measuring the area under the curve as a function of time. Compare the distances found this way with the distances measured directly on the tape.

From the plot of speed versus time, make a plot of acceleration versus time. How good was your early guess as to the times of the greatest and the smallest accelerations?

A falling body certainly accelerates. Tie a block of wood or a weight to the tape of the timer and find its acceleration in $\frac{\text{cm}}{(5 \text{ ticks})^2}$ when it falls freely. Is the acceleration constant?

Figure 1

I-6. *SMALL MASSES*

Matter on the surface of the earth is pulled downward. Our sensitivity to this pull provides a reasonable measure for the amount of matter, a measure which we call mass.

Hold out your hand and have your partner put a book on it. After you get the feeling of the mass of one book, close your eyes and have him place several identical books on your hand. Can you tell how many there are?

Find the mass of your physics text by weighing it on an ordinary equal-arm balance, and estimate the accuracy of your result. Weigh a ball bearing and then a marble on the same balance. Does the accuracy of your measurement, expressed in per cent, increase or decrease with the mass of your object? Try to weigh a hair on the balance; can you determine its mass to within an order of magnitude?

Construct a "soda straw" balance as shown in Fig. 1. Now put a hair a few centimeters long on the end of the arm. Can you see any effect? What happens when you put a tiny piece of paper on the arm?

This sensitive balance must be calibrated if it is to be used as a quantitative measuring device. To do this, divide an easily measurable mass into small parts and calculate their masses. Weigh a writing pad on an ordinary balance. What must you do to find the mass of one square centimeter of one sheet? What assumptions do you make in your calculations? Try using 1 cm^2 pieces of paper to calibrate your balance. If the mass is still too large, cut out smaller pieces. How can you check to see if the masses are about equal? What do you consider the largest source of error in finding the mass of a small piece of paper?

After you have found some equal masses, calibrate your scale by placing them, one by one, on the arm, marking the positions of the balance on the scale. Now weigh a hair, a few grains of sugar, or other things you find interesting. What is the range of your "soda-straw" balance?

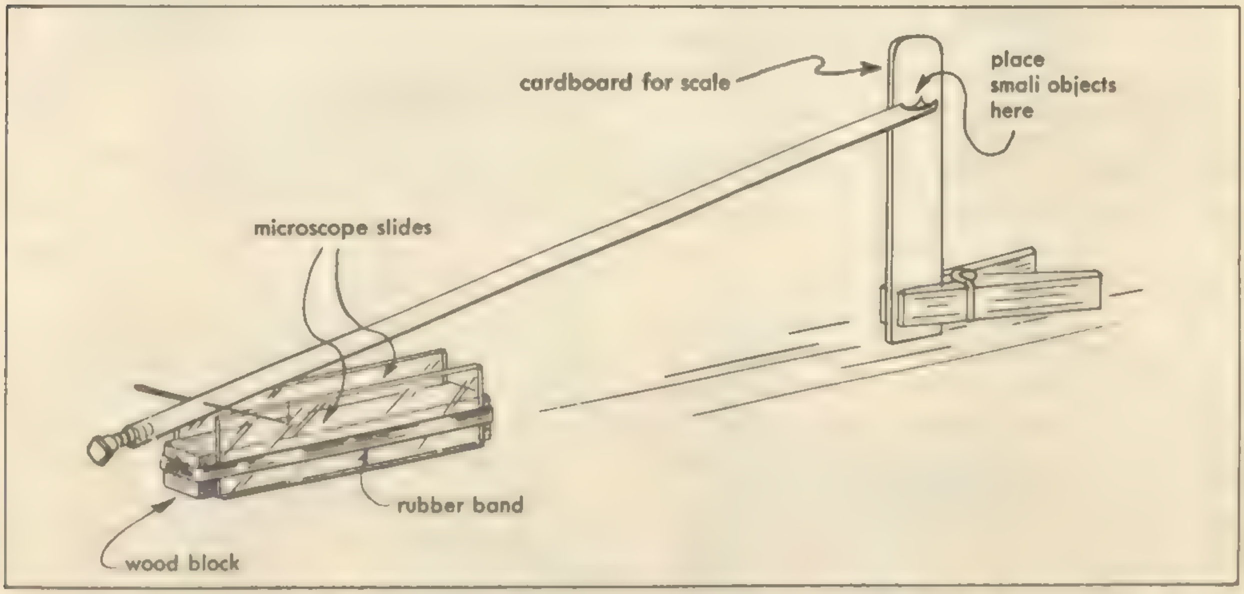


Figure 1. Screw the bolt about half its length into the end of the straw. Determine approximately where this unit balances on your finger or a pencil. Push the needle or long pin through the straw at this point just above the longitudinal axis of the straw. (If the point of support is below the axis, the straw will be unstable and will not balance.) Cut away the top portion of the other end of the straw as shown in the figure.

When the needle is in place, set it across the edges of its support and adjust the bolt (screw either in or out) so the straw points slightly upward.

Set up a scale just behind the long end of the straw as shown. If the balance and scale are placed in a box, deflections caused by air currents will be reduced.

I–7. *THE SPECTRA OF ELEMENTS*

Everybody knows that a few drops of soup or milk spilled onto a gas burner will change the blue gas flame into a mixture of colors, predominantly yellow. Can these colors be used to identify the elements of the substance dropped into the flame? A good way to answer this is to observe the colors produced by known substances.

Since many elements are hard to handle in pure form, we shall use them in compounds. To try only one element at a time, we shall use the same type of compound for each of them. In our case, these will be lithium chloride, sodium chloride, potassium chloride, calcium chloride, strontium chloride, and cupric chloride.

Light a Bunsen burner and adjust it to give a clear blue flame. To get an easily handled amount of salt, heat the wire loop (Fig. 1) in the flame and then dip it quickly into the salt. Some salt will melt and stick to the loop. Now insert the loop into the tip of the inner cone of the flame and notice the predominant color of the flame. Do the same with the other substances, using a new wire for each of them (to avoid confusion, mark the handles of the wires). Does each flame look substantially different?

To increase our ability to distinguish the colors, we shall use a simple spectroscope. Mount the spectroscope on a ringstand with its slit parallel to the flame (Fig. 2). Since the flame of the Bunsen burner is faint, have your partner place the wire in the inner part of the flame. The wire will glow brightly and help you line up the spectroscope. After you have aligned the spectroscope with the flame, move your head slightly sideways until you see the image of the glowing wire in the form of a long band of colors.

Now you are ready to test the various salts

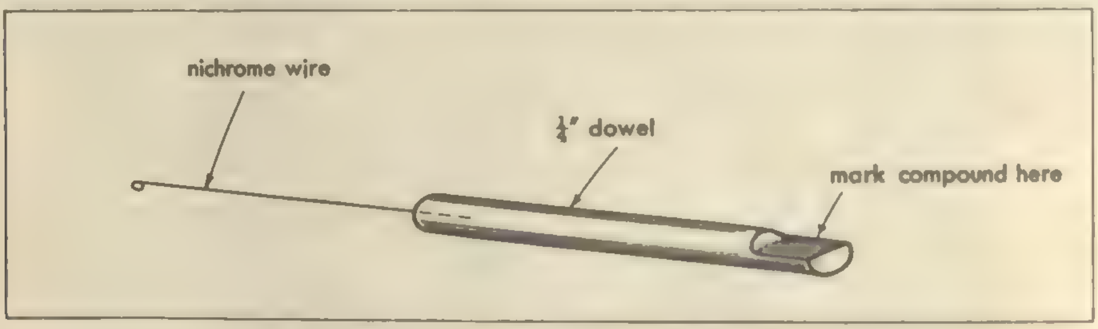


Figure 1

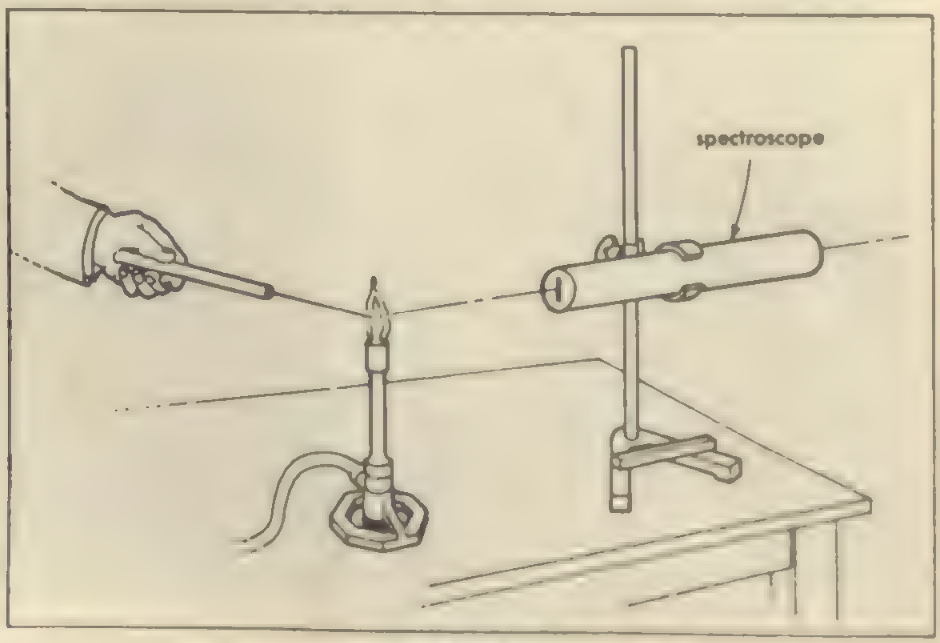


Figure 2

you looked at earlier. Note the details of the colors and compare them with the general impressions you had when you looked at the flame directly. The long band image of the glowing wire can serve as a reference line for the narrow color bars produced by the substances.

Mix two of the salts, say copper and lithium chloride, in a clean container. Can you distinguish the separate colors when looking directly at the flame? (Use a new wire for the mixture.) Can you see them when looking through the spectroscope?

With a different wire, try another mixture of the two salts consisting almost entirely of cupric chloride with only a trace (~5%) of lithium chloride. What do you see without the spectroscope? With the spectroscope? Try a mixture of sodium chloride with a trace of lithium chloride. Can you discover the presence of lithium without the spectroscope? With the spectroscope?

What can you do to convince yourself that the colors you see are really characteristic of sodium, calcium, copper, etc. and not of their chlorides?

Try looking at the colors produced by baking soda and by chalk dust. Can you identify one element in each?

Use your spectroscope to look at light from different sources such as neon and mercury-vapor lamps.

I–8. *MOLECULAR LAYERS*

Molecules and atoms are so small that we cannot see them to measure their size. By using an indirect method, however, we can get an indication of the order of magnitude of the dimensions of some molecules.

A small quantity of oil placed on the surface of water will spread out to form an exceedingly thin film. The thickness of this film is at least equal to the thickness of one oil molecule. Hence if we can find the thickness of the layer of oil, we can conclude that the thickness of the oil molecule is equal to or less than the thickness of the film.

Oleic acid is a good example of an easily available material that will form a thin film. One drop of pure oleic acid dropped into a small swimming pool will cover its entire surface. Of course, if the whole surface of the pool is covered, you are not sure the film could not be thinner. To get the thinnest possible film in a small container, we shall use a drop of a dilute solution of oleic acid in alcohol.

Measure 5 cm^3 of oleic acid and 95 cm^3 of alcohol into a graduated cylinder and place the solution in a clean bottle. Shake the mixture well. Then measure off 5 cm^3 of this solution and mix with 45 cm^3 of alcohol. Calculate the concentration of this solution.

Fill a large, clean, shallow tray with water to a depth of about one centimeter. Dusting the surface of the water lightly with chalk or lycopodium powder will make the film visible. (Chalk rubbed on sandpaper will produce clean chalk dust.)

To make sure the film is caused by the oleic acid and not by the alcohol, drop one or two drops of alcohol in the tank with the eyedropper. What do you observe?

Now use the eyedropper to apply a drop of oleic acid solution. Measure the average diameter of the film and calculate its area. Do two drops form twice the area of one drop? How about three drops? What conclusions do you draw from your answers?

Find out how many drops of this size there are in a cubic centimeter and, using the volume of the drop and the area of the layer, calculate the thickness of the layer. Estimate the accuracy of this calculation, considering the error introduced in each step.

If the thickness of the layer were magnified to 1 cm, how tall would you be on the same scale?

If the layer is considered to be one molecule thick and the molecules are assumed to be essentially cubes, how many molecules would fill one cubic centimeter?

The density of oleic acid is 0.89 gm/cm^3. What is the mass of one molecule?

If you know that the molecular weight of oleic acid is 282, can you calculate Avogadro's number?

I-9. *NATURAL TEMPERATURE SCALE*

The volume of a gas, such as air, changes when the gas is heated or cooled. To see this yourself, fit a one-hole stopper and a 2-inch piece of glass tubing tightly into the neck of a flask (Fig. 1). Hold the flask in your hands for a few seconds to warm the air inside. With a medicine dropper introduce a drop of water into the glass tube and let the flask cool. What happens to the drop of water? Try to control the position of the drop by warming or cooling the air in the flask. (Don't let it fall into the flask.) You might use the position of the drop in the glass tube as a thermometer. But how would you choose a scale for this device?

To set a temperature scale you need temperatures that can be accurately reproduced. Two such temperatures are the boiling and freezing points of water. We shall find the volumes V_1 and V_2 of a given amount of gas at these two temperatures and at the same pressure. You can give the temperatures T_1 and T_2 any two different numerical values you choose. A straight line on a T versus V plot then defines the rest of the temperature scale. The numerical units of the temperature scale are arbitrary.

Immerse a flask in boiling water as shown in Fig. 2. After about 5 minutes, the air in the flask will be at the temperature of boiling water. With your finger firmly over the end of the glass tube (to prevent air from entering the flask) invert the flask in a beaker of ice water (Fig. 3). Remove your finger when the neck of the flask is completely submerged, and cover the entire flask with the ice-water mixture. After a few minutes the temperature of the air in the flask will equal that of the ice water. Why must you make sure that the flask is dry and the fittings are tight?

Before removing the flask from the ice water, make sure the pressure of the air inside the flask equals the pressure of the air in the room. You can do this by adjusting the flask until the level of the water inside and outside the flask are the same. Now place your finger over the end of the glass tube and remove the flask from the ice water. By carefully measuring the volume of the water in the flask and the volume of the flask itself (equipped with stopper and glass tube), determine the volume of air at the boiling point and at the freezing point.

Figure 1

To plot the temperature of the gas versus its volume, draw a pair of perpendicular axes on graph paper. On the horizontal axis mark off a scale for volume and record the two measured volumes V_1 and V_2. On the vertical axis you can mark two points T_1 and T_2 quite arbitrarily. Mark the two points on the paper which represent the volumes and the temperatures at the freezing and boiling points and draw a straight

Figure 2

Figure 3

line through them all the way to the intersection with the temperature axis. This line establishes the relation between volume and temperature.

Now you can choose units for temperature. For example, to get the centigrade scale (generally used in science and also called the Celsius scale), we choose the freezing point 0 and the boiling point 100, and divide the vertical axis into equal parts. What is the temperature in degrees centigrade when the volume is zero?

So far you have constructed an air thermometer. Repeat the experiment, using a different gas, such as oxygen, and plot the results on the same graph. How does the line compare with that for air?

Use this gas thermometer to measure the temperature of tap water and compare the result with that obtained with your air thermometer. Also measure the temperature with a mercury thermometer and see how closely it has been calibrated to agree with the natural temperature scale.

Did you change the temperature of the water by measuring it?

LABORATORY GUIDE

PART II

II-1. *REFLECTION FROM A PLANE MIRROR*

Hold a pencil vertically at arm's length. In your other hand, hold a second pencil about 15 cm closer than the first. Without moving the pencils, look at them while you move your head from side to side. Which way does the nearer pencil appear to move with respect to the one behind it when you move your head to the left? Now move the pencils closer together and observe the apparent relative motion between them as you move your head. Where must the pencils be if there is to be no apparent relative motion, that is, no parallax, between them?

Now we shall use parallax to locate the image of a nail seen in a plane mirror. Support a plane mirror vertically on the table by fastening it to a wood block with a rubber band. Stand a nail on its head about 10 cm in front of the mirror. Where do you think the image of the nail is? Move your head from side to side while looking at the nail and the image. Is the image in front of, at the same place, or behind the real nail? Locate the position of the image of the nail by moving a second nail around until there is no parallax between it and the image of the first nail. In this way, locate the position of the image for several positions of the object. How do the distances of the image and object from the reflecting surface compare?

We can also locate the position of an object by drawing rays which show the direction in which light travels from it to our eye. Stick a pin vertically into a piece of paper resting on a sheet of soft cardboard. This will be the object pin. Establish the direction in which light comes to your eye from the pin by sticking two additional pins into the paper along the line of sight. Your eye should be at arm's length from the pins as you stick them in place so that all three pins will be in clear focus simultaneously. Look at the object pin from several widely different directions and, with more pins, mark the new lines of sight to the object pin. Where do these lines intersect?

We can use the same method to locate an image. On a fresh piece of paper, locate the position of the image of a pin seen in a plane mirror by tracing at least three rays from widely different directions. Mark the position of the mirror on the paper with a straight line before removing it. Where do the lines of sight converge?

Draw rays showing the path of the light from the object pin to the points on the mirror where the light was reflected to your eye. What do you conclude about the angles formed between the mirror surface and the light paths?

Arrange two mirrors at right angles on the paper with a nail as an object somewhere between them. Locate all the images by parallax. From what you have learned about reflection in this experiment, show that these images are where you would expect to find them.

II-2. *IMAGES FORMED BY A CONCAVE MIRROR*

Look at your image in a concave mirror. Is it right side up or upside down? Do the size and position of the image change when you move the mirror toward you or away from you?

To investigate systematically the images formed by a concave mirror, arrange a mirror and a lighted flashlight bulb on a long strip of paper as shown in Fig. 1. Start with the bulb at one end of the paper tape and locate its image by parallax. Is the image right side up or upside down?

Now move the object toward the mirror in small steps, marking and labeling the positions of both object and image as you go. Continue this until the image moves off the end of the tape and can no longer be recorded. How does the change in the position of the image compare with that of the object? Where (on your tape) do you expect the image to be when the object is at least several meters away? Check it. With the object far away, you may find it easier to locate its image by finding where it focuses on a small (1 or 2 cm) piece of paper. The location of the image when the object is very far away is the principal focus of the mirror.

Now place the bulb as close to the mirror as possible and locate the image by parallax. Is it upside down or right side up? Again move the object away from the mirror in small steps, marking and labeling the position of object and image until the image is no longer on the tape.

Measure S_o and S_i, the distances from the principal focus to the object and image respectively, for the pairs of points. Since S_i clearly decreases when S_o increases, try plotting both S_i as a function of $1/S_o^2$ and S_i as a function of $\frac{1}{S_o}$. What do you conclude about the mathematical relation between S_o and S_i?

Where will the image be if the object is placed at the principal focus? Can you see it?

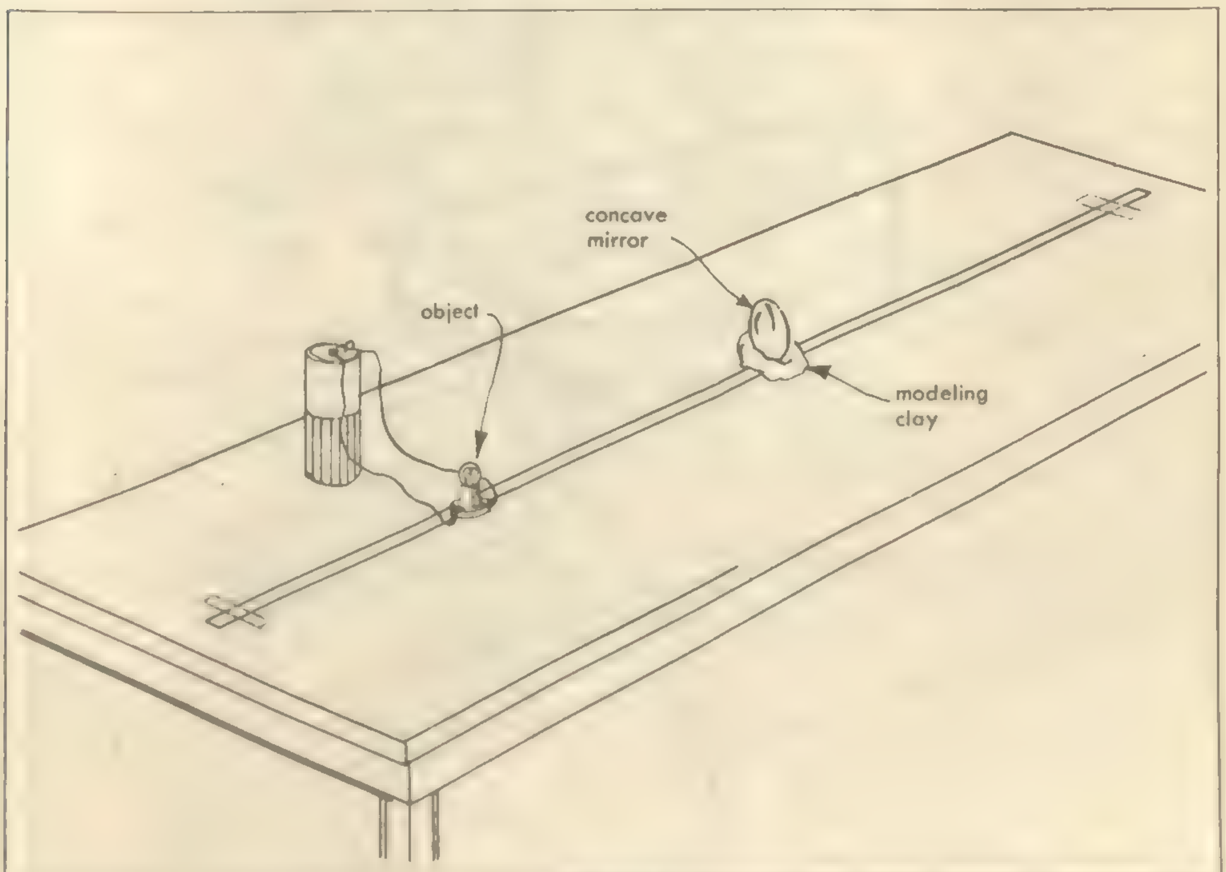


Figure 1

II-3. *REFRACTION*

It is convenient to study the refraction of light in terms of the angle of incidence and the angle of refraction. When light passes from air into water, for example, the angle of refraction is the angle between a ray in the water and the normal to the water surface. In this experiment we shall try to find the relation between this angle and the angle of incidence.

Use a pin to scratch a vertical line down the middle of the straight side of a semicircular, transparent plastic box. Fill the box half full of water and align it on a piece of graph paper resting on soft cardboard as shown in Fig. 1, making sure the bottom of the vertical line on the box falls on the intersection of two lines on the paper. Stick a pin on the line passing beneath the center of the box as shown in the figure. Be sure the pin is vertical.

Now look at the pin through the water from the curved side and move your head until the pin and the vertical mark on the box are in line. Mark this line of sight with another pin. What do you conclude about the bending of light as it passes from air into water and water into air at an angle of incidence of 0°?

Change the position of the first pin to obtain an angle of incidence of about 20°. With the second pin, mark the path of light going from the first pin to the vertical line on the box and through the water. Repeat this for angles of incidence up to about 80°. To ensure a sharp image of the first pin at large angles, it should never be placed more than 4 cm away from the vertical line on the box. (The pinholes give a permanent record of the angles.)

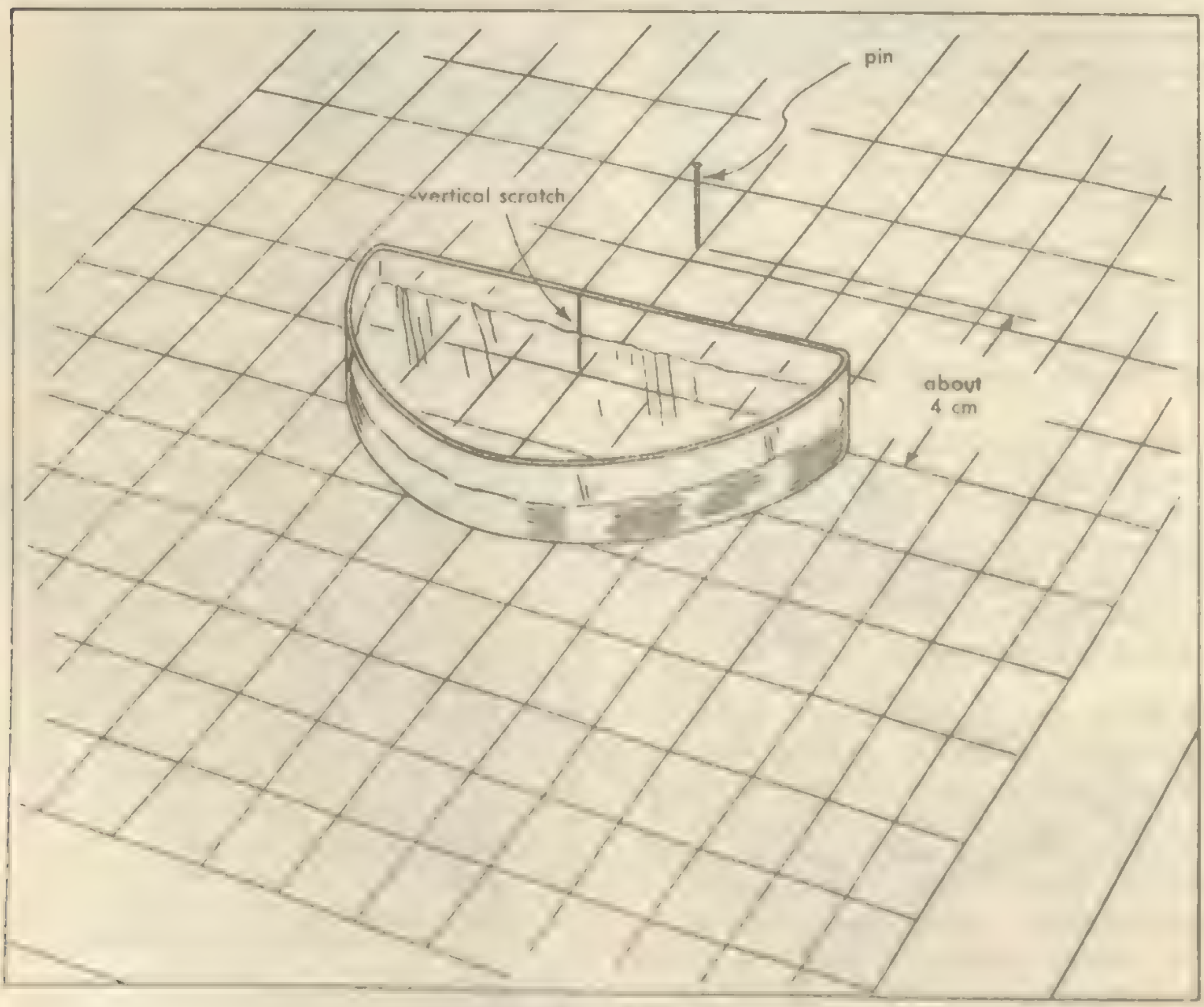


Figure 1

Is the difference between the angles of incidence and of refraction constant? Is their ratio constant?

Draw a large circle around the point where the light rays enter the water and find the ratio of the semi-chord *AC* to the semi-chord *FD* (see Fig. 2) for each case. Since the ratio of the semi-chords is equal to the ratio of the sine of the angle of incidence to the sine of the angle of refraction, it is simpler to find this ratio by measuring the angles and calculating the ratio of their sines.

Plot the ratio of the sines as a function of the angle of incidence. Also plot, on the same graph, the ratio of the angles as a function of the angle of incidence. Which ratio is more nearly constant? What simple mathematical relation do you think best describes the refraction of light?

Is the path of the light through the water the same when its direction is reversed? Investigate this with your apparatus.

Can you predict how light will bend when it goes obliquely through a block of glass with parallel sides?

Repeat the experiment, using another liquid in the box, and plot the ratios of the sines of the angles. Does this liquid refract differently from water?

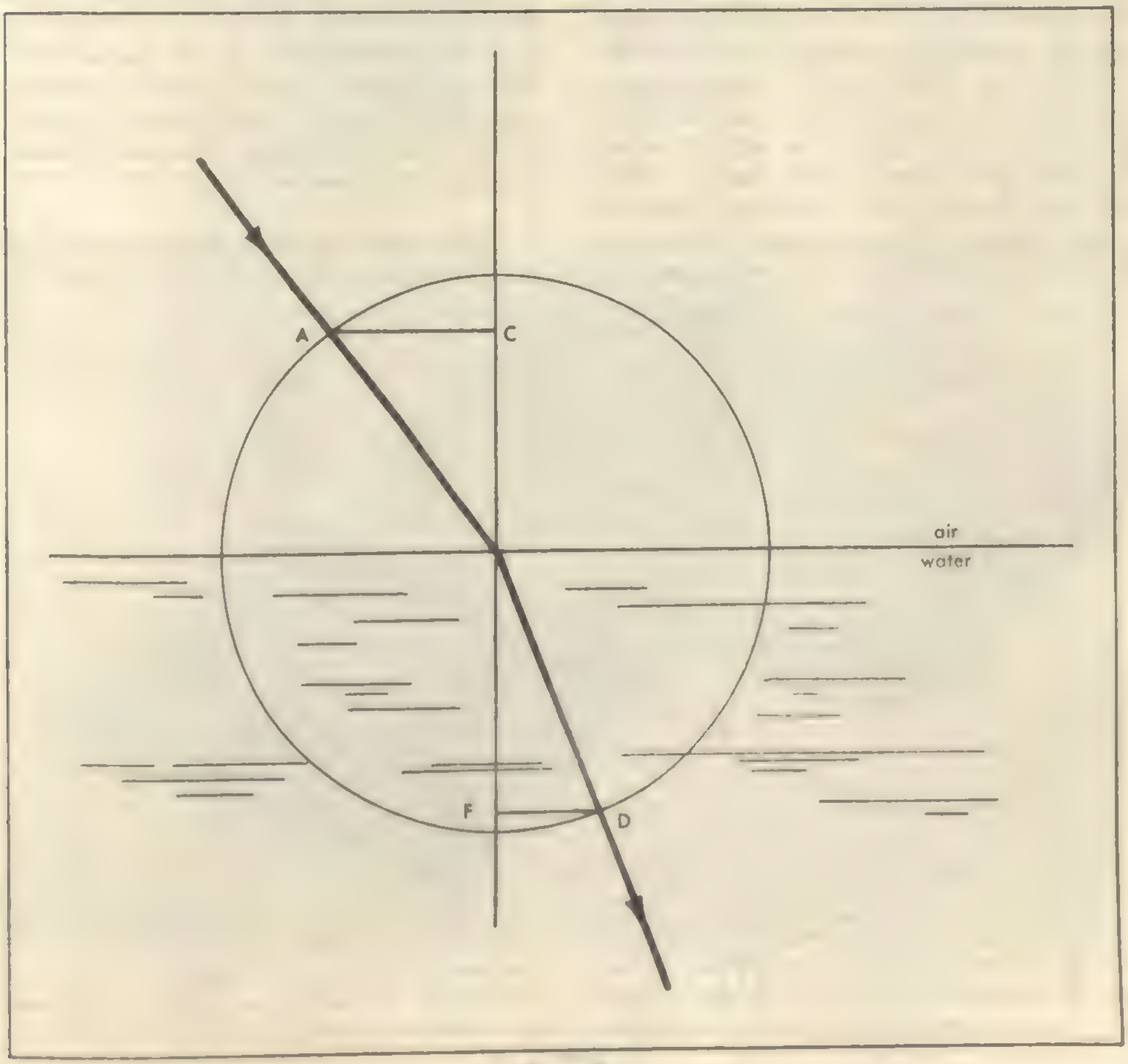


Figure 2

II–4. *IMAGES FORMED BY A CONVERGING LENS*

Look through a converging lens at an object. Is the image you see larger or smaller than the object? Is it right side up or upside down? Do the size and position of the image change when you move the lens with respect to the object?

To investigate the images formed by a converging lens, arrange a lens and a lighted flashlight bulb on a long strip of paper as shown in Fig. 1. Start with the bulb at one end of the paper tape and locate its image by parallax. Is the image right-side up or upside down?

Now move the object toward the lens in small steps, marking and labeling the positions of both object and image as you go. Continue this until the image moves off the end of the tape and can no longer be recorded. How does the change in the position of the image compare with that of the object? Where (on your tape) do you expect the image to be when the object is at least several meters away? Check it. With the object far away, you may find it easier to locate its image on a piece of paper. The location of the image when the object is very far away is the principal focus of the lens. How can you convince yourself that the lens has two principal foci, one on each side and at the same distance from the center?

Now place the bulb as close to the lens as possible and again locate the image by parallax. Is it upside down or right side up? Again move the object away from the lens in small steps, marking and labeling the positions of object and image until the image is no longer on the tape.

Measure S_o and S_i, the distance from the principal foci to the object and image, respectively, for the pairs of points. (The distance S_o is measured from the principal focus on the object side of the lens and S_i is always measured from the principal focus on the opposite side from the object.) Since S_i clearly decreases when S_o increases, try plotting S_i as a function of $1/S_o$. What do you conclude about the mathematical relation between S_o and S_i?

Where will the image be if the object is placed at the principal focus? Can you see it?

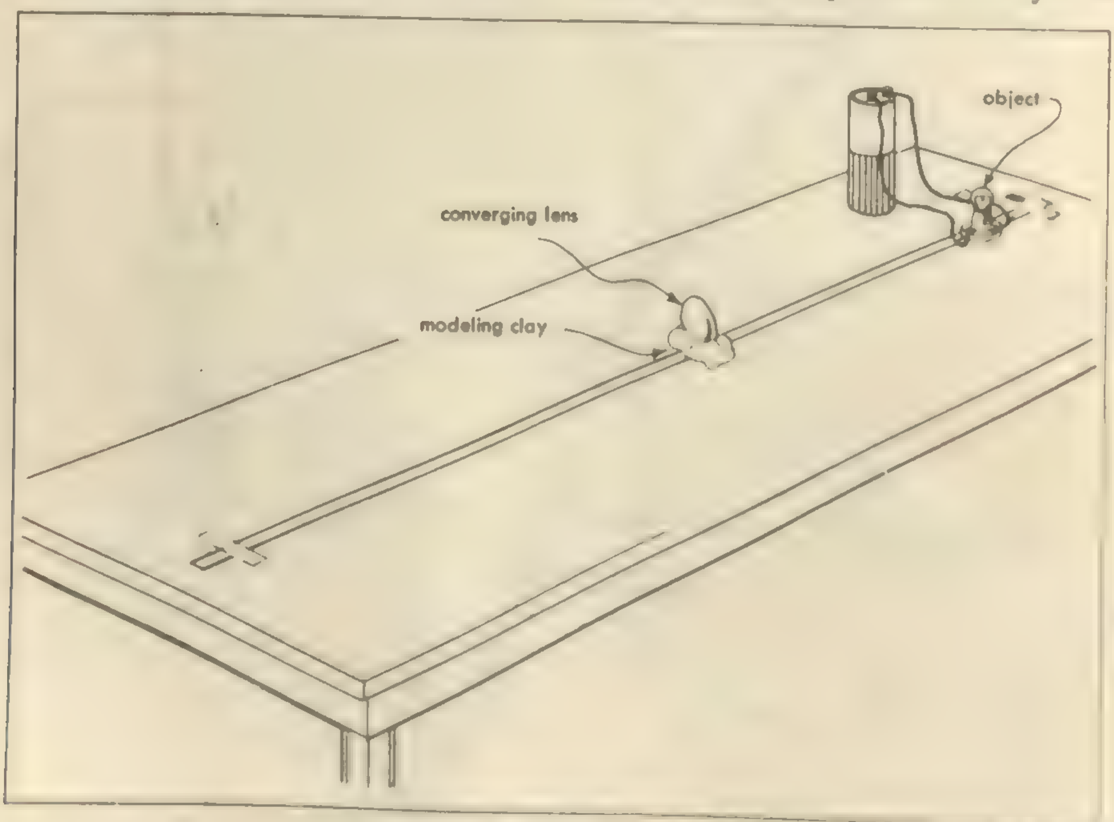


Figure 1

II-5. *THE "REFRACTION" OF PARTICLES*

A steel ball rolling across a horizontal surface moves in a straight line at nearly constant speed. If the ball intercepts a slope obliquely, the speed it gains as it rolls down the slope will change its direction. At the bottom of the slope it will move off in a straight line in a direction different from its original direction.

The path of a ball moving this way resembles the path of light as it is refracted in going, for example, from air into glass. In going from the top to the bottom of the slope, the ball changes direction; at the interface between two media, light changes direction. In the model, therefore, the upper level corresponds to one medium (air); the lower level corresponds to the other medium (glass); the slope corresponds to the interface between them. We shall examine the paths of "refracted" particles to see if they change direction according to Snell's law, with the apparatus shown in Fig. 1.

Roll a steel ball down the full length of the launching ramp on the upper level so it strikes the slope obliquely. Remove the carbon paper and, for identification, label the tracks made by the ball on the upper and lower planes. Repeat the procedure five or six times at different angles of incidence, always being careful to start the ball from the same point on the launching ramp to give it the same initial speed each time.

Measure and record the angles of incidence and refraction as measured from normals to the horizontal edges of the slope. Can this change in direction of the ball be described by Snell's Law? What does this particle model of light predict about the speed of light in water compared to its speed in air?

Could you make a "lens" that will focus rolling balls?

Figure 1. Arrange two horizontal surfaces connected by a short slope. Make sure that the two surfaces are level. Tape a sheet of white paper on each surface so the edges coincide with the top and bottom edges of the slope and place sheets of soft carbon paper over the white papers.

II—6. *THE INTENSITY OF ILLUMINATION AS A FUNCTION OF DISTANCE*

The particle model of light predicts that the intensity of illumination from a point source will be inversely proportional to the square of the distance from the source. We shall test this prediction by measuring the illumination at different distances from a light source.

When we place a pencil between a screen and two light sources *A* and *B*, arranged as shown in Fig. 1, both sources will throw a shadow of the pencil on the screen; each source will illuminate the shadow of the other. With both shadows close together or slightly overlapping, their illuminations can be accurately compared. If we move source *B* toward or away from the screen until both shadows appear equally bright, the illumination from *A* and *B* will then be equal.

If we place two identical bulbs at *A*, we will assume that the illumination on the screen due to *A* is double the illumination from one bulb. We must then move *B* closer to the screen to obtain equally illuminated shadows. If we use three bulbs at *A*, we must move *B* still closer to obtain equally illuminated shadows. By changing the illumination on the screen due to *A* by known multiples, we can find how the illumination from *B* varies with its distance from the screen.

Before starting the experiment, make sure that each of the bulbs you are going to use at *A* gives the same illumination on the screen. How will you do this?

Using one, two, three, and four bulbs

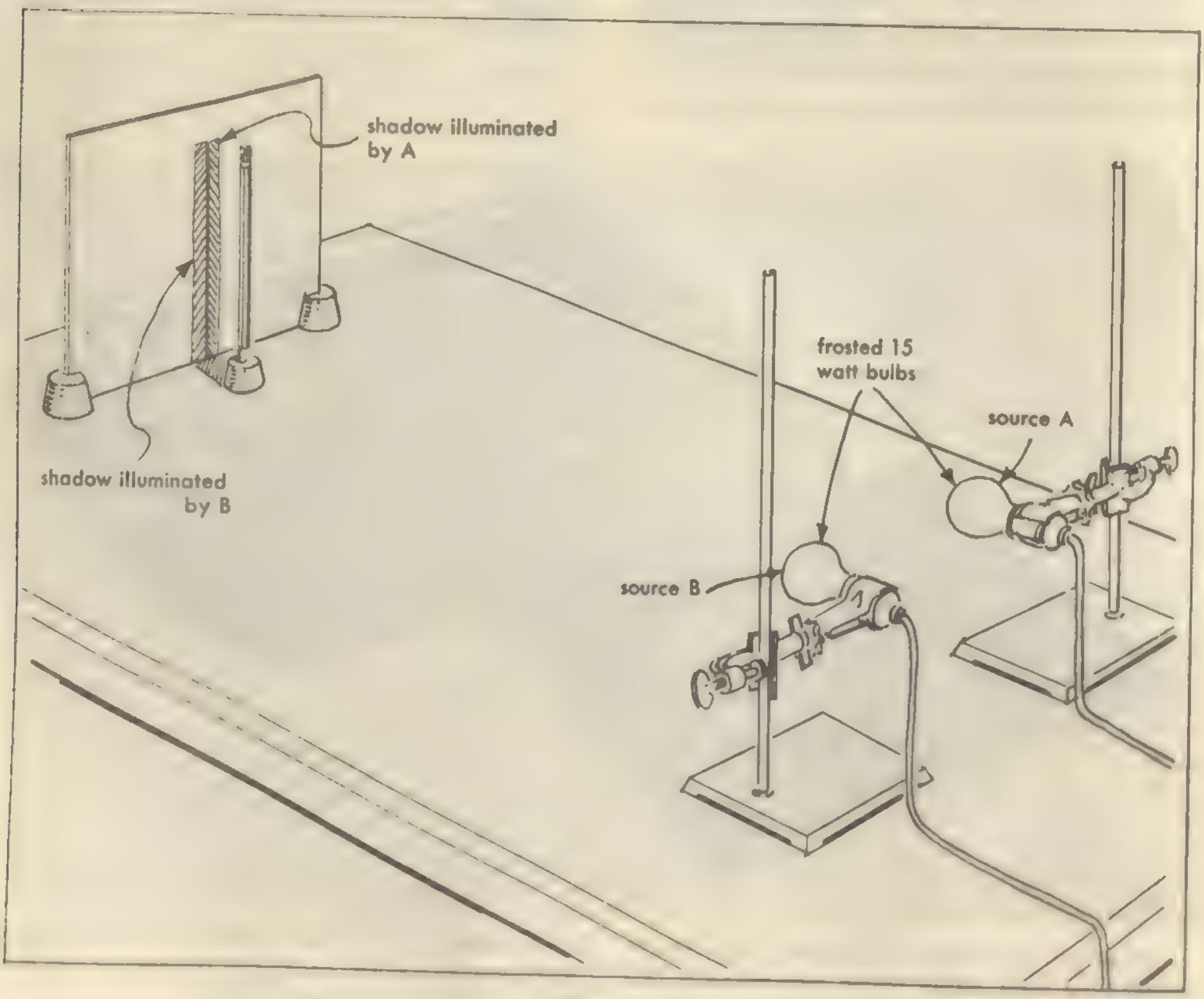


Figure 1

stacked vertically as shown in Fig. 2, find the distances at which bulb B must be placed to give illuminations equal to the different illuminations from A. Why must the bulbs be stacked vertically?

Do your results verify the inverse-square law as predicted by the particle model? Does background illumination on the screen, such as the reflection from a white shirt or light from your neighbor's apparatus, cause errors in your results?

Can you use the apparatus to determine if a 60-watt bulb has four times the source intensity of a 15-watt bulb?

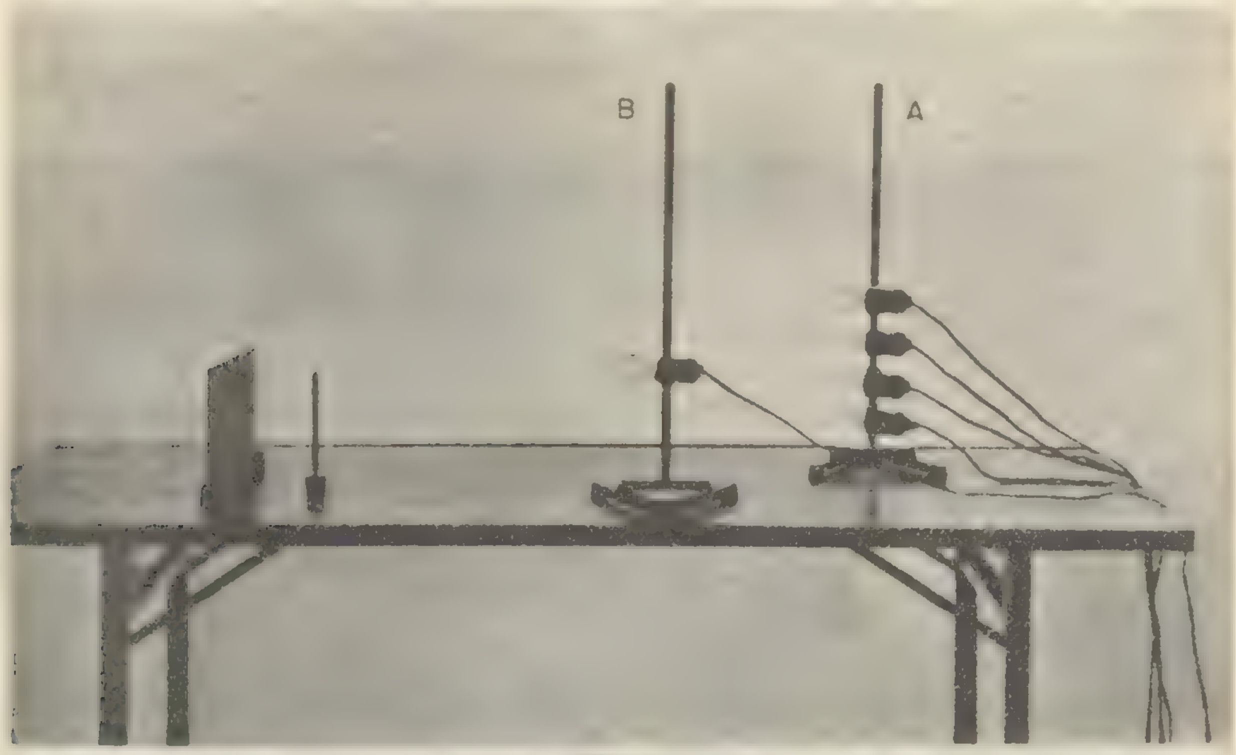


Figure 2

II-7. *WAVES ON A COIL SPRING*

You have probably seen various kinds of waves but have not experimented with them. With this experiment you will begin a detailed study of waves.

While your partner holds one end of a coil spring on a smooth floor, pull on the other end until the spring is stretched to a length of about 10 meters. With a little practice you will learn to generate a short, easily observed pulse. Look at the pulse as it moves along the spring. Does its shape change? Does its speed change?

Shake some pulses of different sizes and shapes. Does the speed of propagation depend on the size of the pulse? To find the speed more accurately you can let the pulse go back and forth a few times, assuming that the speed of the pulse does not change upon reflection. How do you check this assumption?

Change the tension in the spring. Does this affect the speed of the pulse? Would you consider two springs of the same material stretched to different lengths to be the same or different media?

You and your partner can send two pulses at the same time. What happens to the pulses as they collide? Try it with pulses of different sizes and shapes, traveling along the same side and along opposite sides of the spring.

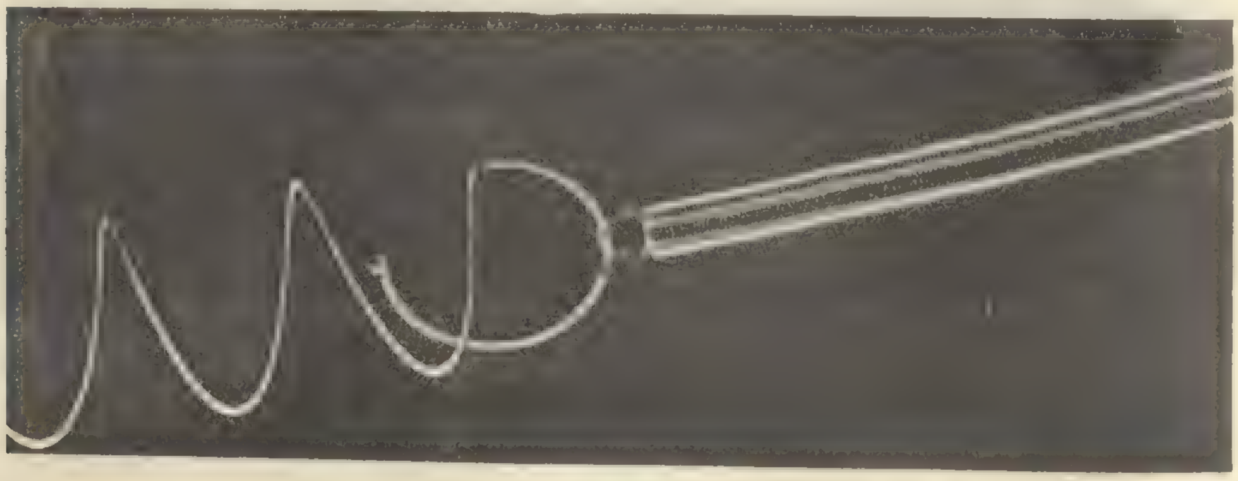


Figure 1

When the pulses meet, how does the maximum displacement of the spring compare with the maximum displacement of each pulse alone? You can determine the largest displacement of an individual pulse by moving your hand a measured distance as it generates the pulse. A third partner can mark with chalk the largest displacement of the spring when the pulses meet.

We can investigate the passage of waves from one medium to another by tying together two coil springs on which waves travel with different speeds (Fig. 1). Send a pulse first in one direction and then in the other. What happens when the pulses reach the junction between the two springs?

Tie a spring to a long, thin thread (Fig. 2). How does a pulse sent along the spring reflect when it reaches the thread? How does this reflection compare with that at a fixed end? Is the speed of the pulse on the thread larger or smaller than that on the spring?

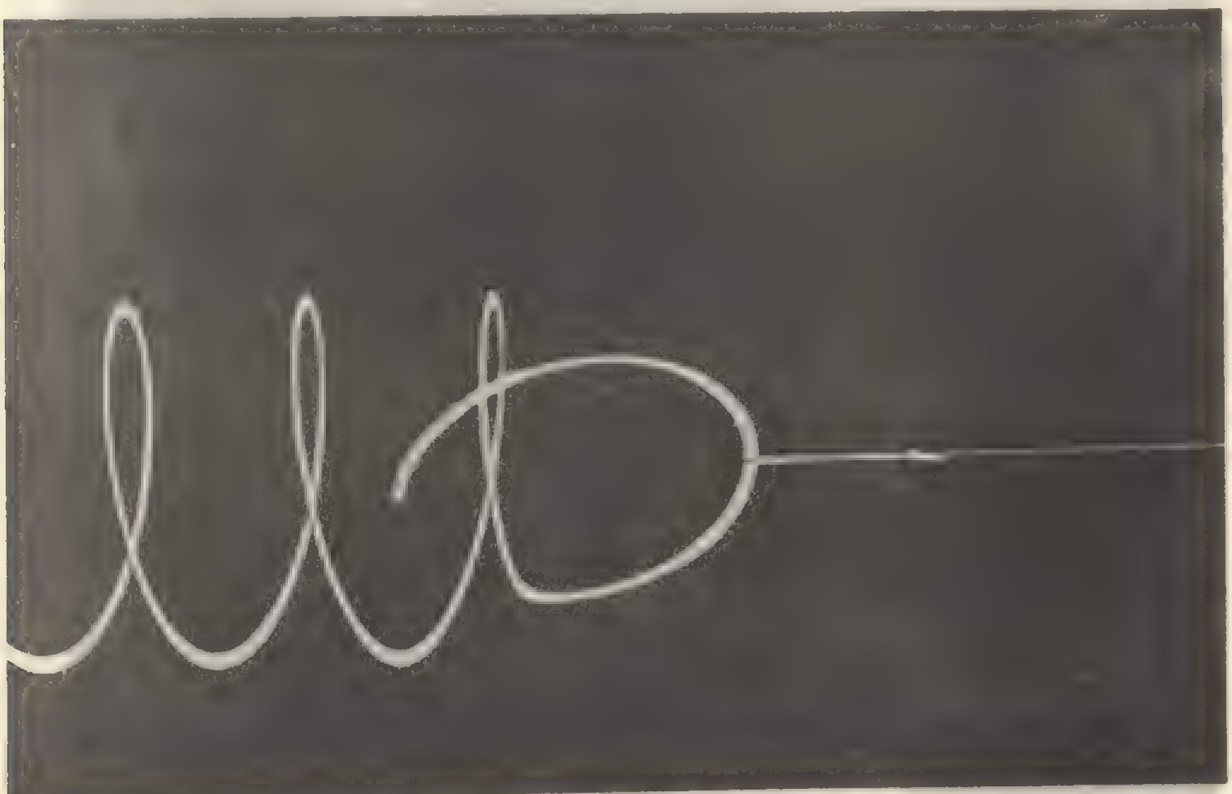


Figure 2

Figure 1. (Insert shows how damper is placed.)

II–8. *PULSES IN A RIPPLE TANK*

Set up a ripple tank, screen, and light source as shown in Fig. 1. Fill the tank with water to a depth of $\frac{1}{2}$ to $\frac{3}{4}$ cm and measure the depth at all four corners to be sure the tank is level.

You now have a very handy tool for studying the behavior of waves; it has an advantage over the coil spring, since the direction of propagation of the waves is not restricted to a line. To see this, just touch the water with your finger tip. What is the shape of the pulse you see on the screen? Is the speed of the pulse the same in all directions?

You can also generate straight pulses in the ripple tank by rolling a long rod through a fraction of a revolution in the water. (Place your hand flat on top of the rod and then move it forward about a centimeter.) Practice making such pulses until you can make ones that give sharp, bright images on the screen. Do the pulses remain straight as they move along the tank?

Place a straight barrier in the tank and generate pulses that strike it at an angle of incidence of 0°. In what direction do they reflect? Reflect pulses at different angles of incidence. Are the reflected pulses straight? How does the angle of reflection compare with the angle of incidence?

Instead of making direct measurements to answer the last question quantitatively, you can study a few situations which will clearly demonstrate the relation between the two angles. For example, observe how a circular pulse reflects from a straight barrier. Can you locate the virtual source of the reflected pulse (the image of the source of the incident pulse)? How would you explain the result?

Bend a length of a large diameter rubber tubing as shown in Fig. 2. The shape you give it is very close to a parabola. What do you observe when you use this tubing as a reflector for straight pulses in the tank? Find the focus of the parabola from the reflection of straight pulses and mark it on the screen. Try to follow the motion of several small segments of the pulse. How would you indicate the direction of motion of each segment? How does your way of indicating this relate to light rays? Are the rays representing the initial direction of the pulse parallel to each other?

Generate circular pulses at the focus of the parabola. What is the shape of the reflected pulse? Are there other points which will give the same result? What must you assume about the relation between the angles of incidence and reflection to explain your observations?

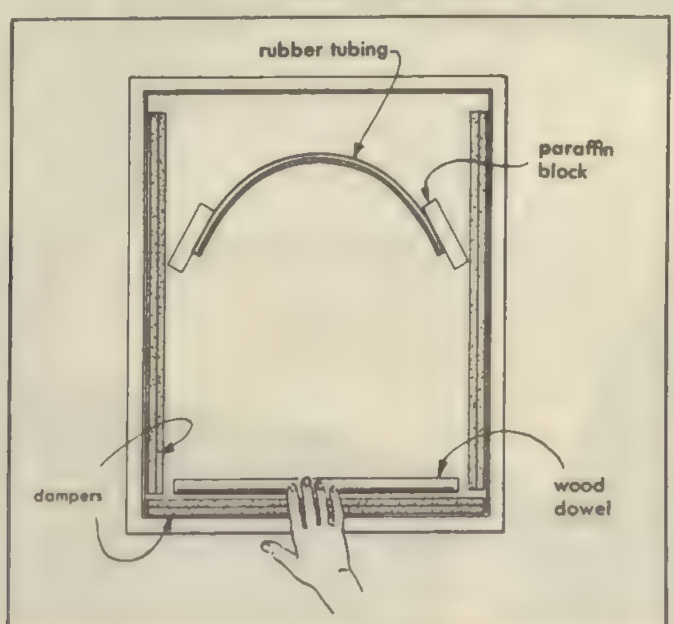


Figure 2

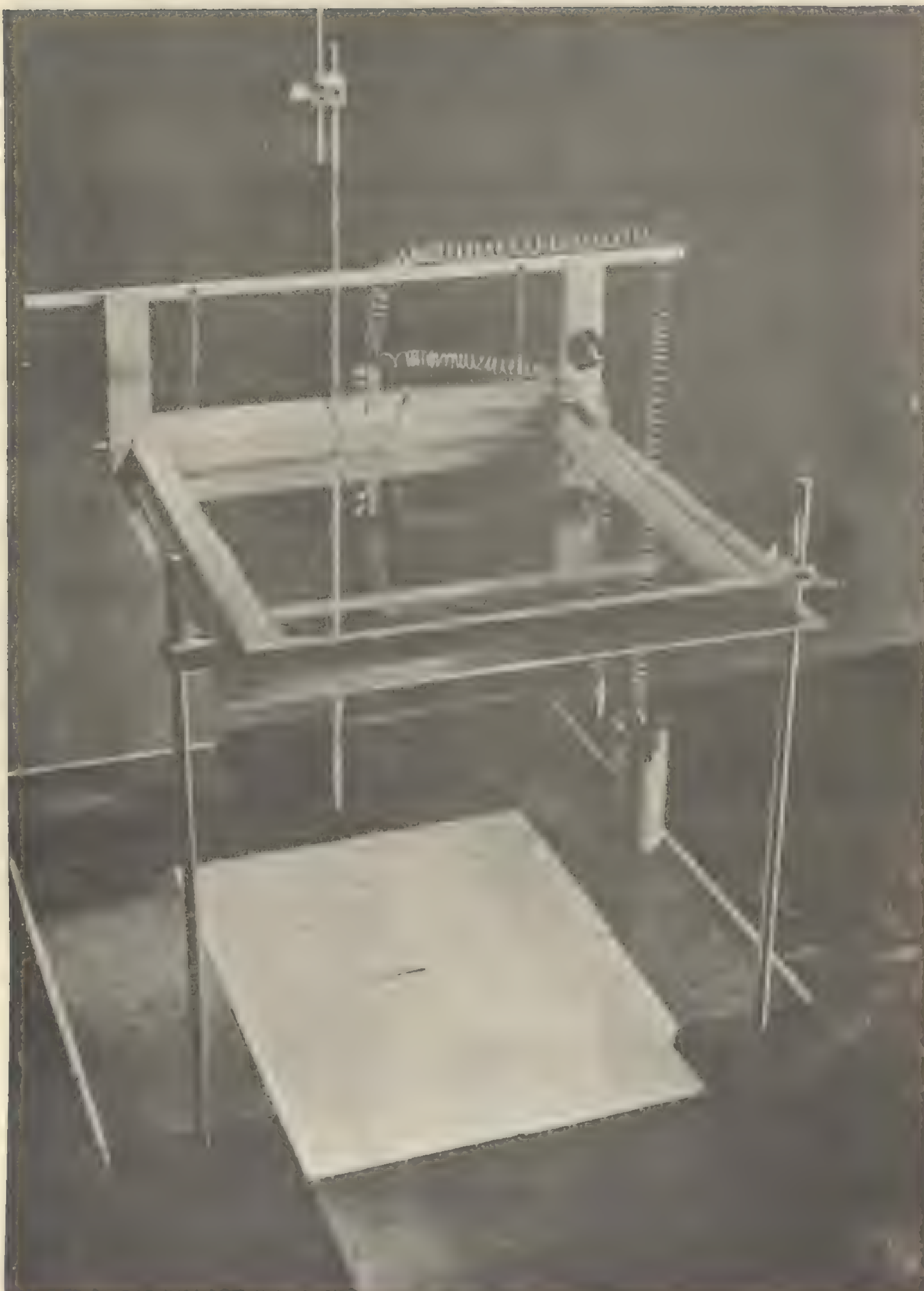


Figure 1

II-9. *PERIODIC WAVES*

The relation $v = f\lambda$ for the speed, frequency, and wave length of a periodic wave holds for all periodic waves. We shall now apply this relation to waves in the ripple tank and on a coil spring.

Set up the straight wave generator as shown in Fig. 1 (the water should be $\frac{1}{2}$ to $\frac{3}{4}$ cm deep). Practice using it at various frequencies. Look at the waves through your stroboscope (2 or 4 open slits) and "stop" their motion.

Adjust the wave generator to a low frequency and have your partner help you measure the frequency of rotation of the stroboscope while you "stop" the waves. How is this frequency related to that of the waves?

To find the wave length, "stop" the wave pattern with the stroboscope and have your partner place two pencils or rulers parallel to the waves and several wave lengths apart.

Make several measurements of frequency and wave length and calculate the speed of propagation. How accurate is your determination of the speed? Notice that you have measured the wave length of the image of the waves on the screen. How is this apparent wave length related to the true wave length of the water waves?

The wave pattern may also be stopped by placing a barrier in the middle of the tank as shown in Fig. 2. The incident and reflected waves superpose to give a stationary pattern—that is, a standing wave. How does the distance between two bright bars in the standing wave compare with that in the traveling wave? Can you measure the wave length from the standing wave pattern?

Can you detect a change in speed when the depth of water is changed to about 2 cm?

Moving your hand only slightly, shake a periodic wave into a coil spring. Adjust the frequency until a standing wave builds up. By measuring wave length and frequency, determine the speed of the wave on the spring.

Without changing the length of the spring, can you produce standing waves of any wave length you choose?

If you have two coil springs on which pulses travel at different speeds, hook them together, end to end. Try to generate a standing wave in both. Fix one end of the pair and shake the other end. How do the frequencies, the wave lengths, and the speeds in the two media compare?

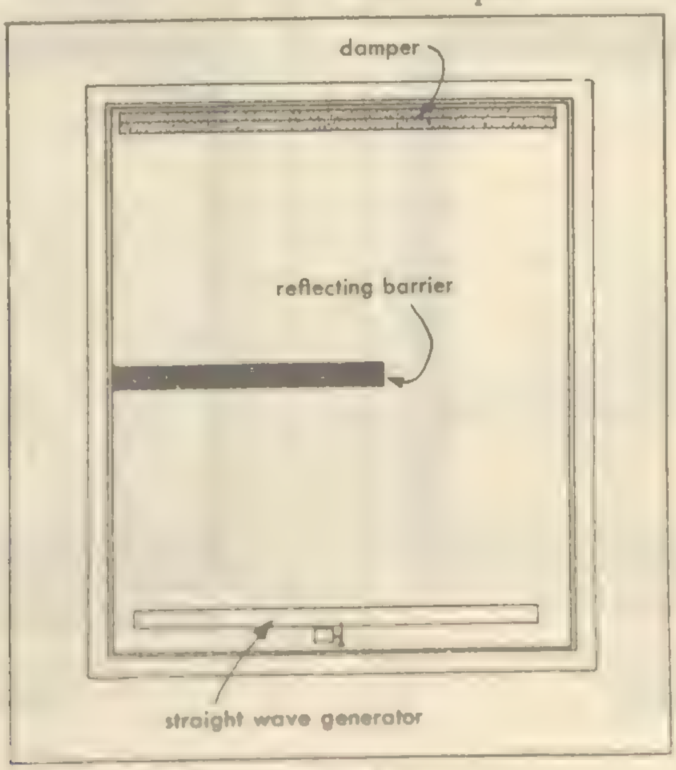


Figure 2

II-10. *REFRACTION OF WAVES*

In Experiment II–9 we found that the speed of water waves depends on the depth of the water. Two different depths of water therefore constitute two different media in which waves can be propagated. This suggests that water waves can be refracted, for example, by allowing them to travel from deep water into shallow water.

Support a glass plate in the ripple tank so its top surface is at least 1.5 cm above the bottom of the tank. Add water to the tank until it is no more than 0.2 cm deep over the glass plate. Be sure the depth of the water is uniform over the glass plate.

What do you predict will happen if straight periodic waves originating in the deep water cross into the shallower water when the boundary between the two media is parallel to the wave generator (Fig. 1)? Using very low-frequency waves, check your prediction with a stroboscope.

Now turn the glass plate so that the boundary is no longer parallel to the incident waves (Fig. 2). Are the refracted waves straight? How does the angle of refraction compare with the angle of incidence? How do the wave lengths in the two sections compare? What about the speeds? While keeping the generator running (to keep the frequency constant) try other angles of incidence.

Does a wave model agree with the refraction of light better than a particle model if we consider in which medium the speed of light is greater?

To establish the quantitative relation between the angles of incidence and refraction requires considerable care. Keeping the frequency constant, you can measure the angle of refraction for four or five different angles of incidence. Over what range should you choose the angles of incidence? What do you conclude from your results?

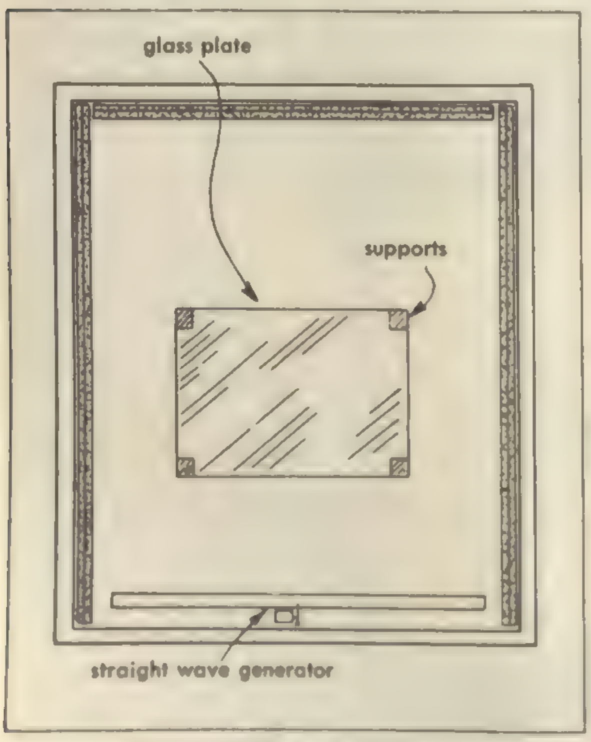


Figure 1

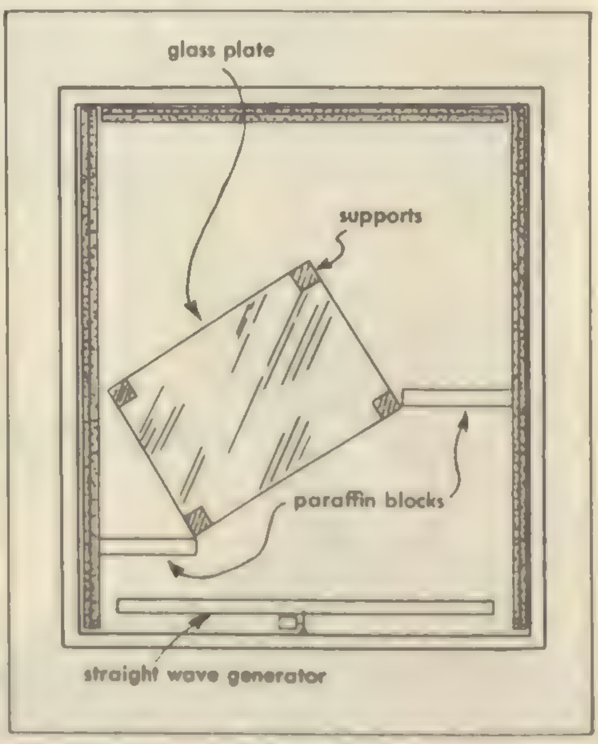


Figure 2

II-11. WAVES AND OBSTACLES

An opaque object placed in the path of a parallel beam of light will cast a sharp shadow on a screen behind it. The shadow will be the same size as the object. What happens when we place an obstacle in the path of a straight wave?

Place a small, smooth paraffin block in the ripple tank about 10 cm from the straight wave generator (Fig. 1), and generate periodic waves of long wave length. Do the waves continue in their straight path on both sides of the block? Could you sense the presence of the block by looking at the pattern only near the far end of the screen? Does the block cast a sharp shadow?

How is the pattern behind the block affected when the wave length is reduced by increasing the frequency? (To obtain clean waves at high frequency, the generator must be very smooth. Make sure there are no bubbles on its edge.) At high frequency the pattern is best seen by viewing it through the stroboscope with all slits open. Under what conditions would you expect the block to cast a sharp shadow?

We can let a parallel beam of light pass through a small opening. If a screen is held behind the opening we shall see a light spot equal in size to the opening.

You can produce an analogous situation in the ripple tank (Fig. 2). Are waves of long wave length still straight beyond the slit? Do the waves continue to move in their original direction? What happens when you decrease the wave length step by step? Show in a few sketches how the pattern changes.

Now that you have observed the effect of the wave length on the wave pattern behind the slit, how does changing the width of the slit affect the pattern? Try it with a medium wave length. How must you adjust the wave length to compensate for the change in pattern?

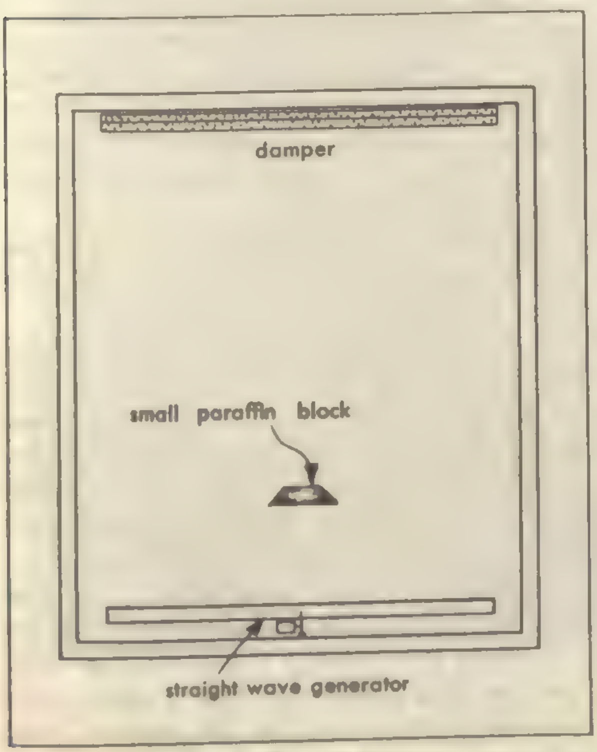


Figure 1

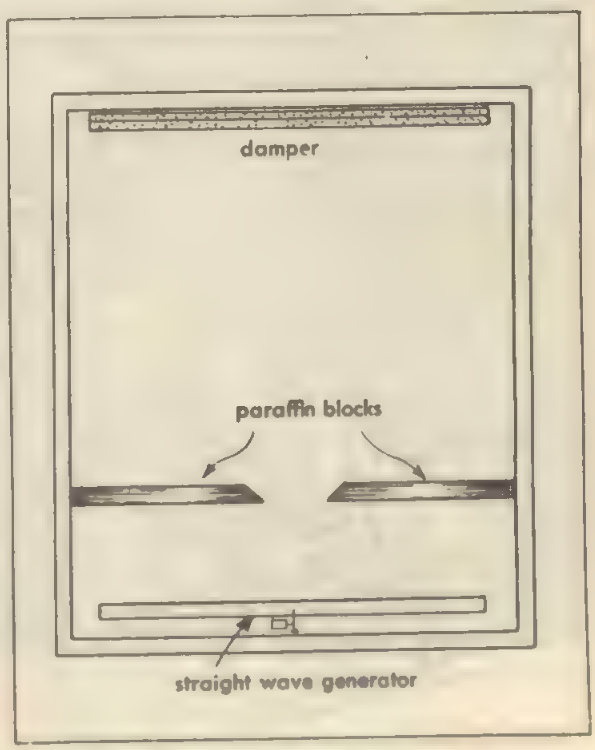


Figure 2

II–12. *WAVES FROM TWO POINT SOURCES*

What will happen if two point sources near each other generate periodic waves of the same frequency? Try it in the ripple tank with the two point sources attached to the straight wave generator about 5 cm apart. How would you describe the resulting pattern? Are there regions where the waves from the two sources cancel each other at all times? How does the pattern change when you change the frequency?

Change the distance between the sources without stopping the motor (to keep the frequency as nearly constant as possible). How does this affect the pattern?

By applying the principle of superposition you have learned that for two point sources in phase, the direction of the nth nodal line far from the sources is given by

$$\sin \theta_n = \frac{x}{L} = (n - \tfrac{1}{2})\frac{\lambda}{d}.$$

Check this prediction by finding the wave length from the above relation, measuring x, L, n, and d, and comparing it with a direct measurement of the wave length.

You will recall that straight waves passing through a narrow slit are strongly diffracted. If the slits are narrow enough they will act like point sources. Can you repeat the present experiment using the straight wave generator and two slits made with an arrangement of paraffin blocks?

II–13. *INTERFERENCE AND PHASE*

In the last experiment we investigated the interference pattern produced by two point sources in phase. In this experiment we shall learn how a change in the phase delay between the two point sources affects the direction of the nodal lines in the interference pattern.

A generator in which the phase delay can be adjusted is shown in Fig. 1. Choose a separation between the sources and a wave length similar to those used in the preceding experiment, and set the sources in phase. Do you obtain the same kind of pattern you obtained with your regular generator?

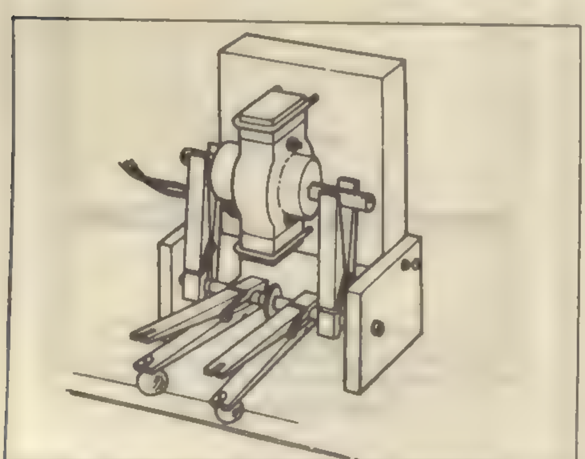


Figure 1. The two dowels on both sides of the motor are mounted off center. If both are up at the same time, the sources are in phase. If one is up when one is down, the phase delay is one half.

Now change the phase in small steps and observe the change in the direction of the nodal lines. Using the in-phase pattern as a reference, how does the position of the first nodal line change, as you change the phase delay from zero to one? How does the position of the second nodal line change?

How would you expect the interference pattern to look if you could change the phase of the sources while the generator operates?

You can change the phase delay between two sources, with only a very short interruption of the waves, by using the two generators shown in Fig. 2. Pluck the ends of the two coat hangers; observe the formation of nodal lines as waves spread out. Are the nodal lines stationary? Do the two sources have the same frequency?

After you have adjusted the frequencies to be the same, pluck the ends of the wires. When the waves have reached the end of the tank, stop one wire briefly and pluck it again. Did you change the phase of the two sources? Keep plucking the ends of the hangers alternately. What happens to the nodal lines?

What would you expect to see if you could change the phase of the two sources very rapidly?

Figure 2. Each point source is made from a coat hanger with a bead and alligator clasp fastened as shown. Moving the sliders serves to adjust the frequency. It is important that the sources be strongly clamped to heavy bases.

II–14. *YOUNG'S EXPERIMENT*

We have seen the interference pattern made by two point sources in the ripple tank. If we look at two light sources in phase, we would expect to see light of maximum intensity in certain directions and no light in other directions (the directions of the nodal lines). From the direction of the nodal lines and the separation of the sources we can calculate the wave length of light.

Two narrow slits illuminated by a showcase lamp will provide the two sources. Their preparation is explained in Fig. 1. Look through the slits toward the filament of the light bulb from a distance of about 2 meters. Using Fig. 2, explain why you see dark and light bars.

Can you suggest why the bars near the end of the pattern are colored? How does covering part of the bulb with red cellophane affect the pattern?

Now cover the whole bulb with red cellophane and place a ruler slightly above it as shown in Fig. 3. How will you determine $\sin \theta_n$ for the farthest nodal line that is easily visible? By measuring the thickness of one of the razor blades with the optical micrometer, you can determine the separation of the slits. What is the wave length of red light?

Repeat your measurements to find the source of the largest error. How accurate is your determination of the wave length?

Cover part of the bulb with red cellophane and part with blue. Which color has the shorter wave length?

How is the interference pattern affected when you turn the slide to form a horizontal angle of about 30° with the line of sight, instead of 90°? How do you explain this?

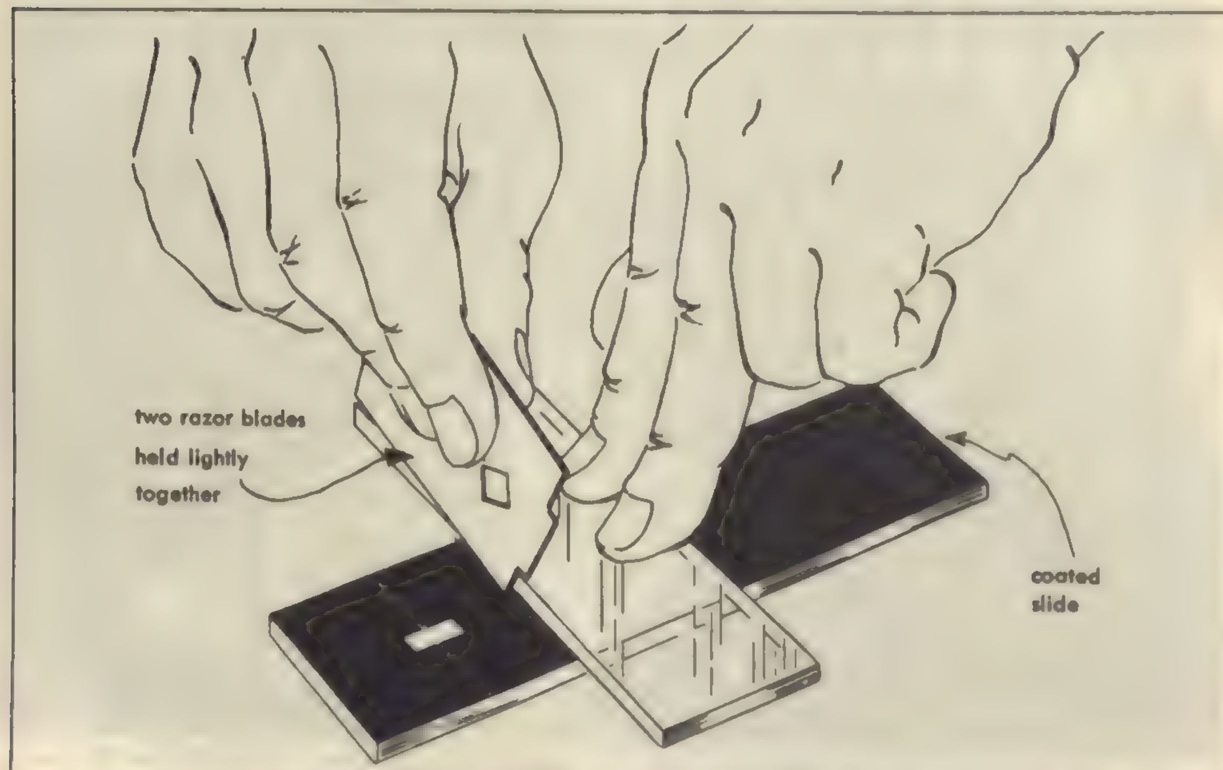


Figure 1. Coat a glass slide with a colloidal suspension of graphite and let it dry. Scratch a pair of slits as shown, holding the razor blades lightly together and using little pressure. Make several pairs of slits. Select for use those which show at least three clear, white lines when you look at the showcase lamp. Scratch a "window" across each pair of slits. This will enable you to see the pattern through the slits and read a scale at the same time.

To prevent damage to the slits, it is worth while to cover the coated slide with a plain slide and tape them together.

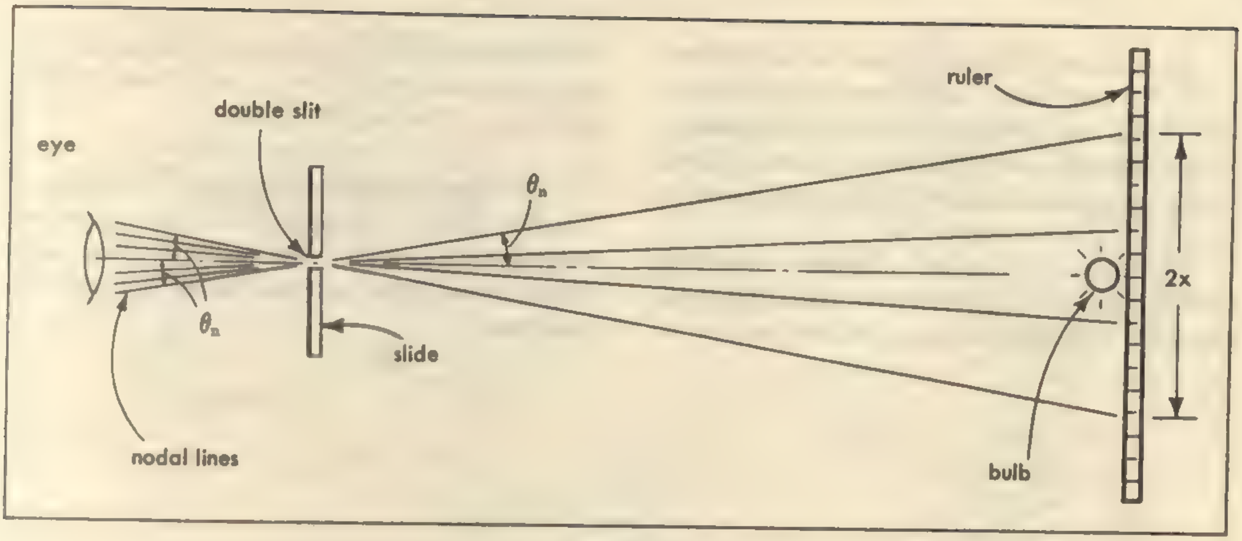


Figure 2

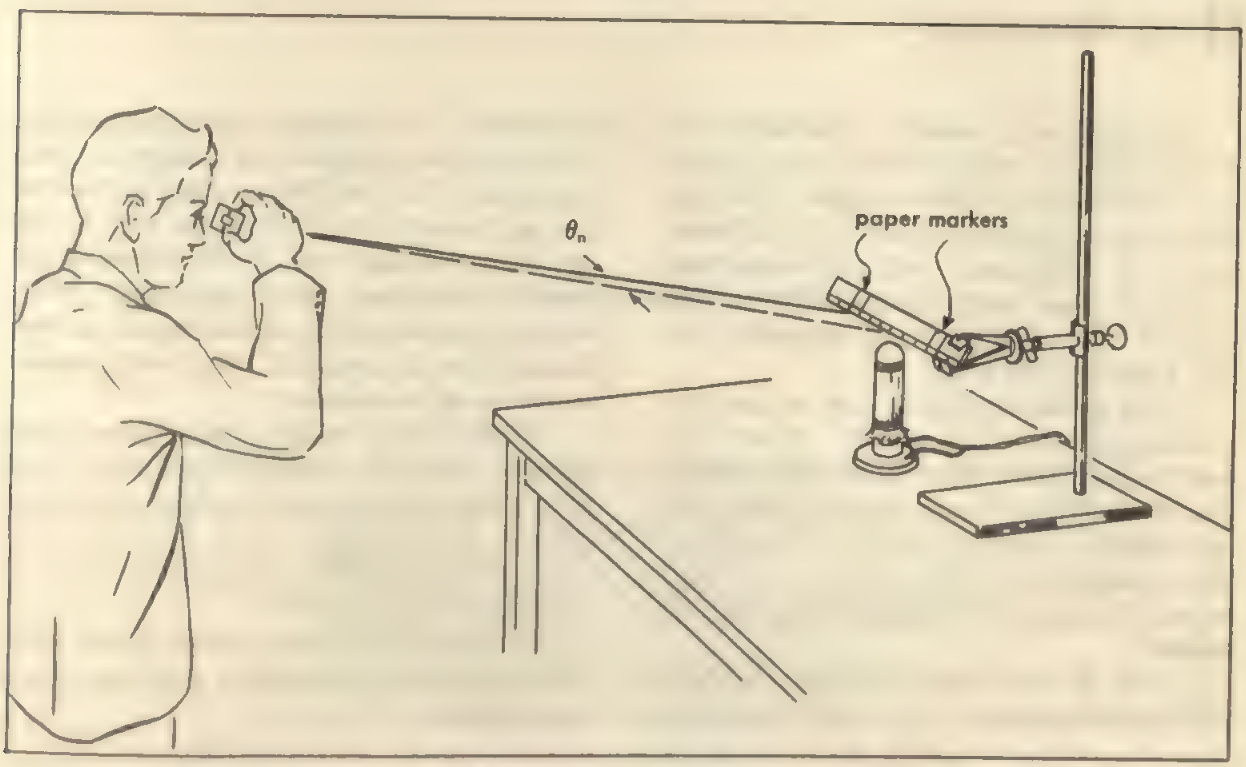


Figure 3. The interference pattern and the paper markers on the ruler can be seen simultaneously by looking through the slits and the "window" at the same time. The cellophane is held by rubber bands.

II—15. *DIFFRACTION OF LIGHT BY A SINGLE SLIT*

In preparing the double slits for Experiment II–14 you may have made some single slits inadvertently and noticed that they also showed a pattern of dark and light bars. To study them further, scratch several single slits, using both a needle and a razor blade.

Compare the pattern obtained with the double slits with the pattern of the single slits. Use both white and red light. As you look at the bulb through a double slit, try blocking off one slit of the pair by holding a razor blade behind the slide. What happens?

It is quite difficult to measure the width of the slits directly. However, you can determine it by using the value you found for the wave length of red light, and the theory of single-slit interference.

II—16. *RESOLUTION*

We can study resolution qualitatively by looking through small apertures at two small light sources that are close together. The light sources can be tiny holes in aluminum foil placed in front of a ripple-tank bulb, and the apertures we look through can be holes of different sizes punched in another piece of aluminum foil. Fig. 1 shows such a setup.

Look at the two sources with one eye from a distance of about one meter. Be sure that bright light, directly from the filament, reaches your eye through the two holes that make up the two sources. Can you resolve the sources into two separate points of light with your eye? How large is the aperture through which you view the sources?

Look at the sources through one of the middle-sized apertures. Can you resolve the two sources? Now increase your distance from the sources and observe the change in their appearance. Find the distance where the sources are just resolved. At this distance look at the two sources through each of the different-sized apertures and sketch their appearances. Why does the resolution of the sources depend on their distance from the aperture? Why does it depend on the size of the aperture?

While looking at the sources through the aperture that just resolves them, have your partner hold first red and then blue cellophane in front of the sources. How does the wave length of the light affect the resolution? How do you explain this effect?

How would the sources appear if they were larger but the distance between their inner edges was the same?

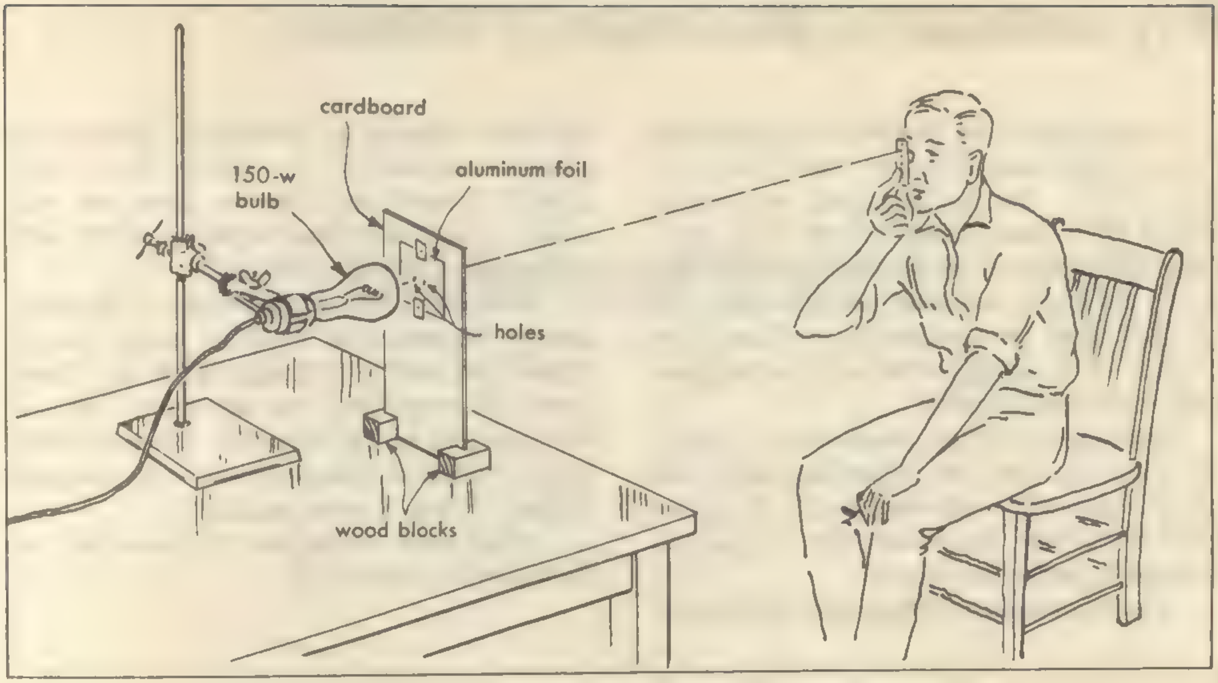


Figure 1. To make the sources, use a needle to punch two holes about $\frac{3}{4}$ cm apart in a piece of aluminum foil. Mount the foil directly in front of the filament of the 150-watt bulb.

The holes through which the sources are viewed are shown at the right. To make these holes, puncture a strip of foil with the tip of a needle, making the largest hole the thickness of the needle and the smallest just large enough to see light through.

II-17. *MEASUREMENT OF SHORT DISTANCES BY INTERFERENCE*

A thin layer of air between two glass plates produces light effects similar to those seen on a soap bubble. To see this, place two freshly cleaned glass plates, about 20 cm long, on a black background. Darken the room and illuminate the plates with green or yellow light. If the glass plates are very flat you will see a few irregular bands of light reflected from the glass. What causes these bands?

Press down on the plates with a pencil. Can you make one of the bright bands move and take the place of an adjacent band? If so, how much closer have you pushed the top plate to the bottom one at that point?

You can measure the thickness of a piece of very thin material by inserting it between the plates at one end (Fig. 1). Be sure that the material is smooth and that the plates are very clean. (Hold the plates together tightly with rubber bands close to each end.)

How much does the separation of the plates change between two adjacent bright bands? Count the number of bright bands in a 2-cm span. (A magnifying lens may help.) What is the thickness of the material? Compare your result with that obtained with a micrometer caliper. Which is more accurate?

What limits the range of thickness that can be measured in this way?

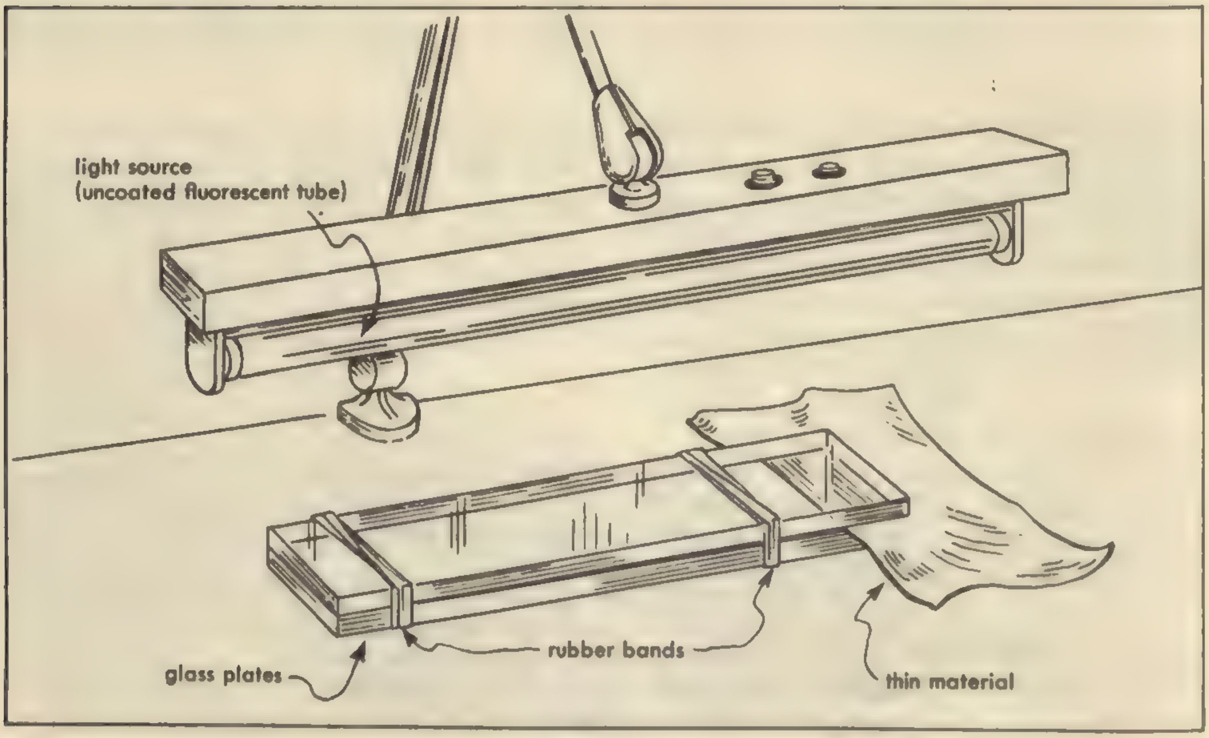


Figure 1

LABORATORY GUIDE

PART III

Figure 1

III-1. A VARIATION ON GALILEO'S EXPERIMENT

Galileo argued that an object moving horizontally would continue to move horizontally forever at constant speed (Text, Section 20–2). He supported this argument with his observation that an object accelerates when it moves down an incline and decelerates when it moves up, reaching nearly the same height it had when it started. We can perform a similar experiment with a pendulum, observing the fall of the pendulum bob on one side of its swing and its rise on the other.

Suspend a pendulum about 3 m long from the ceiling or a suitable stand. Clamp the pendulum thread 40 or 50 cm above the bob so it swings from this point and not from where it is suspended (Fig. 1). Bring the bob sideways until it is a measured distance *d* above the lowest level of its swing. Let it go. Compare the distances the bob travels on either side of the lowest point. How does the highest level reached after release compare with the height from which the bob was released?

Now, instead of letting the pendulum swing through a normal arc, interpose a barrier so that, when released, the pendulum swings from the barrier (Fig. 2). What do you predict about (a) the horizontal distance the bob will travel upon release, (b) the level to which it will rise? Try it.

Next, with the barrier in the same place and the clamp at various positions ranging from the initial one to the point of suspension, let the bob go from a measured height above the lowest level of its swing. Determine how high it rises at the end of its swing and roughly measure the distance from the center point. Give each pendulum length several trials. Be sure to let the bob go from the same position each time.

From your data, can you make a conjecture about the height and the horizontal distance the bob should reach from the same point of release if the pendulum could be made 10, 50, or thousands of meters long?

What do your results suggest would happen to a ball moving on a perfectly smooth, horizontal surface?

Do you think perpetual motion is possible?

Figure 2

III–2. *CHANGES IN VELOCITY WITH A CONSTANT FORCE*

We know qualitatively from everyday experience that we must apply a force to move an object from rest or to change its velocity while it is moving, but we are not so sure of the quantitative relation between the velocity changes and the force we apply. We can investigate this relation with the apparatus shown in Fig. 1. Be sure to clamp the bumper tightly to the table so that it can stop a heavy cart.

The cart, loaded with bricks and running on roller-skate wheels, can be pulled forward with a constant force by hand. To make sure this force is constant, we apply it through rubber strands which are kept stretched at a constant length as the cart is pulled along. As it moves, the cart pulls a strip of paper tape under the striker of an electric bell timer clamped to the table edge. From these tapes we can then find the velocity at different points on a run and can plot a curve of the velocity of the cart as a function of time.

The experiment is best performed on a smooth, level table. If necessary, level the table with wedges under the legs and check with a spirit level. Crumbly bricks may be wrapped in aluminum foil or wrapping paper to keep their grit from getting on the table.

Before making runs to find how the velocity changes with a constant force, you should be sure that the cart moves with a nearly constant speed when you do not pull it. Load the cart with two bricks and make several tapes with the timer, giving the cart different initial pushes. Look carefully at the tapes. Is the velocity more uniform when the cart moves slowly or when it moves rapidly?

Now you can study the effect of a constant pull on the motion of the cart. Attach one end

Figure 1

of a rubber loop to the cart as shown in Fig. 2. Hook the other end of the rubber loop over the end of a meter stick. While your partner holds the cart, extend the meter stick forward alongside the cart until the rubber loop stretches to a given total length—say 80 cm. Your partner starts the timer and a few seconds later, on signal, releases the cart. You move forward, pulling the cart while keeping the rubber strands stretched to the 80 cm mark. You will find it worth while to make a few practice runs.

Now attach the paper tape to the cart loaded with two bricks and run off a tape. From this tape, plot a graph of the velocity as a function of time (see Experiment I–5). It is not necessary to use all the marks on the tape in calculating the velocity. Instead, use groups of ten marks for a convenient unit time interval, measuring the velocity in meters per ten "ticks." Analyze only that portion of the tape which represents the part of the run where you are reasonably sure the force you applied was constant.

Run off another tape using four bricks on the cart and the same rubber loop. Plot the data from this tape on your original graph. What do you conclude about the acceleration produced by a constant force?

Is the force exerted the only force acting on the cart?

Was the acceleration greater or smaller when a larger mass was accelerated?

Figure 2

III–3. *THE DEPENDENCE OF ACCELERATION ON FORCE AND MASS*

The change in velocity of an object is proportional to the time interval during which a constant force acts on it. In other words, a constant force produces a constant acceleration. This we found in the last experiment. Here we shall investigate quantitatively how different forces accelerate a given mass and how a given force accelerates different masses.

Acceleration Caused by Different Forces

Using one, two, three, and four rubber loops (Fig. 1, Experiment III–2) to produce the accelerating force, make tape recordings of the motion of the cart when it is loaded with four bricks. Find the acceleration from the tapes and plot a graph of acceleration as a function of the force, that is, the number of loops.

Since we know from the last experiment that the acceleration is constant for a constant force, it is not necessary to calculate the acceleration for many different intervals in the same run. To see this, consider a body starting from rest with a constant acceleration a. In a time t, it moves a distance d given by $d = \frac{1}{2}at^2$. Hence, $a = \frac{2d}{t^2}$. If the various runs extend over the same time, the acceleration in each case, therefore, is proportional to the distance moved. Measure the distance traveled from rest in the same time interval on each of your tapes. For the fixed time interval use a number of ticks that will give a distance long enough to provide accurate results. (Don't use a distance so long that it includes the last part of the motion where it is difficult to keep the force constant.)

What do you conclude from your graph? What can you say about the ratio of force to acceleration in this part of the experiment?

Assuming no friction in the apparatus, should the graph pass through the origin? Where, with respect to the origin, would you expect your graph to pass?

The Effect of Mass on the Acceleration Produced by a Constant Force

With one rubber loop find the acceleration of the cart when it is loaded with two, three, and four bricks. Plot a graph of the ratio of force to acceleration as a function of the number of bricks.

What do you conclude from your graph? Do you have enough points on your graph to make it convincing? If you have time, try accelerating one brick and five bricks and include the results on your graph.

From your graph, can you express the mass of the cart alone in terms of the mass of the bricks?

How could you find the mass of a chunk of lead or a heavy stone using the apparatus? Try it.

III-4. *INERTIAL AND GRAVITATIONAL MASS*

The inertial balance, a simple device for measuring the inertial mass of different objects, is shown in Fig. 1. The frequency of its horizontal vibration depends on the inertial mass placed on the balance.

Put different quantities of matter on the platform and qualitatively observe the periods of vibration of these masses. Is the period greater or smaller for larger masses? How do the accelerations of the different masses compare when the platform is pulled aside about 2 cm and released? Does this seem to be in accord with Newton's law of motion?

Find the quantitative relationship between the quantity of matter on the balance and the period of vibration by plotting a graph of the period as a function of the mass. You may do this in the following way:

First, measure the period of the balance alone by measuring the time for as many vibrations as you can conveniently count. Since the period of the balance is very short, it is difficult to count the vibrations visually. Hold a small piece of paper near one of the hacksaw blades and count the audible snaps made by the paper when the blade just ticks it. You may find it is easier to count in groups of three or four vibrations.

Select six nearly identical objects or unit masses such as C clamps. Now measure the period of the balance loaded with each of the six C clamps (Fig. 2). How many vibrations should you time and for how many seconds should you time them to make sure that your error is no greater than about 2 per cent? To within what per cent do the clamps have equal inertial masses?

Now find the periods with one, two, three . . . unit masses on the balance and from these data plot the period as a function of the mass (number of clamps) on the balance.

Measure the period of an object of unknown mass, of different material and shape—a stone, for example. Using the clamps as unit masses, find the inertial mass of the stone. Now by ordinary weighing find the gravitational mass, in grams, of each of the clamps. To within what per cent do they have the same gravitational mass? Try to predict the gravitational mass of the stone from your previous measurements. Check it by weighing the stone. Is your predicted value within the estimated experimental error of your inertial balance?

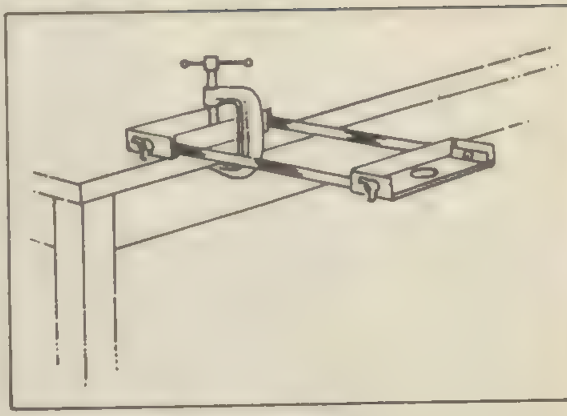


Figure 1

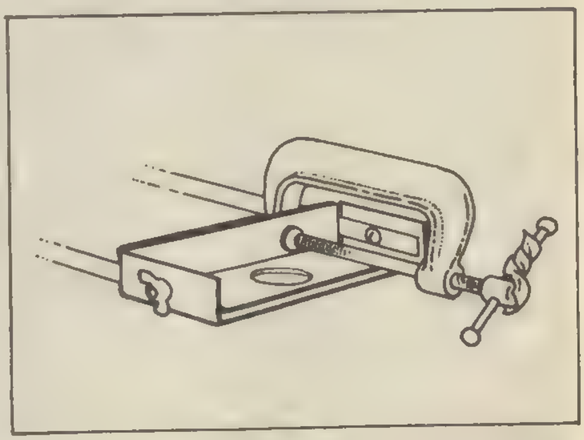


Figure 2

If you had found similar results with other objects, what would you conclude about gravitational and inertial mass? Are they equal? Proportional? Independent? Must the units of inertial mass be the same as those for gravitational mass? How would the results of this experiment be changed if you did the experiment on the moon?

To discover experimentally whether or not gravity plays a part in the operation of the inertial balance, load it with the iron slug. This can be done by inserting a wire through the center hole of the slug and setting the slug into the

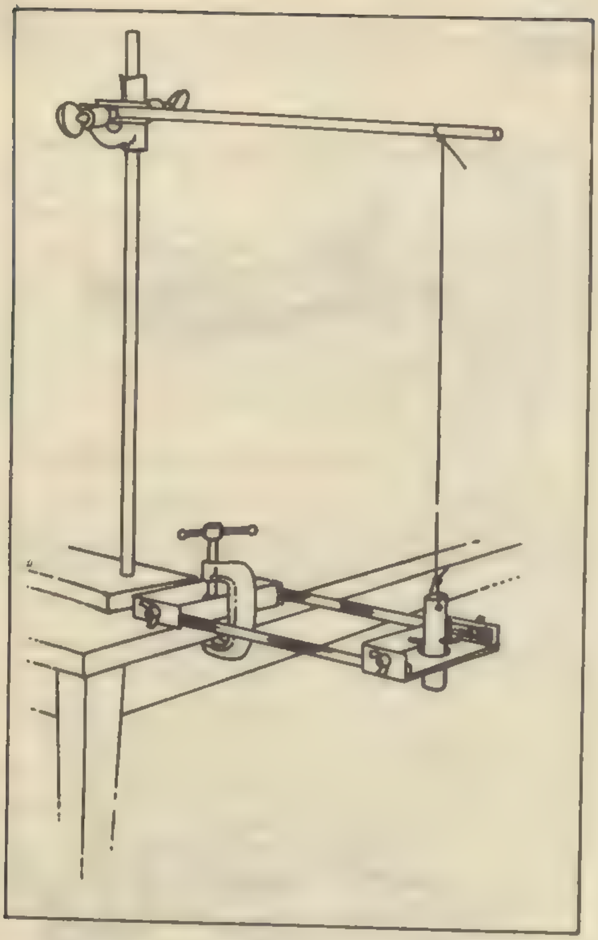


Figure 3

hole in the platform. The slug then rests on the platform. Measure the period of the loaded balance.

Now lift the slug slightly so that its mass no longer rests on the platform and hold it in this position by a long thread tied to a ring-stand (Fig. 3). How do the periods compare in these two cases?

Would the period be different if the inertial balance were mounted as shown in Fig. 4?

How could this device be used to measure the acceleration of an automobile?

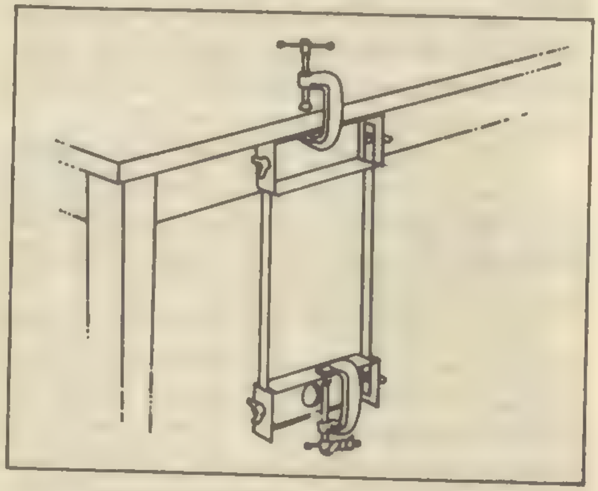


Figure 4

III-5. *FORCES ON A BALL IN FLIGHT*

Fig. 1 is a multi-flash photograph of projectile motion. It was made by throwing a small ball into the air at an angle of 27° with the horizontal. The time interval between successive exposures was 1/30 sec and the ball moved from left to right in the picture. The ball's trajectory looks like those described in Section 21–3 of the text.

Examine the photograph. Is the horizontal velocity of the ball constant? What can you conclude about the resultant force acting on the ball if the horizontal velocity is not constant?

If we analyze the photograph in detail and find the changes in velocity caused by the resultant force, we will learn more about the forces acting on the ball than we can learn from a casual examination of the photograph.

Analyze the velocity changes which occur during successive 0.1 sec time intervals (three intervals on the photograph) in the following way: Clip transparent centimeter graph paper or tracing paper on top of the photograph and mark the center of each image. Draw straight lines connecting every third point. These lines represent the displacement of the ball during each 0.1 sec and are therefore a measure of the average velocities during these equal time intervals. To find the velocity changes in each of these intervals we can add the *negative* of one velocity vector to the next velocity vector. For example in Fig. 2 (a), $-\vec{v}_1$ is added to $\vec{v}_2$ to give the change in velocity $\Delta\vec{v}$.

Is the direction of the velocity change the same in each interval? Are the magnitudes of

Figure 1. Scale: 1 to 10

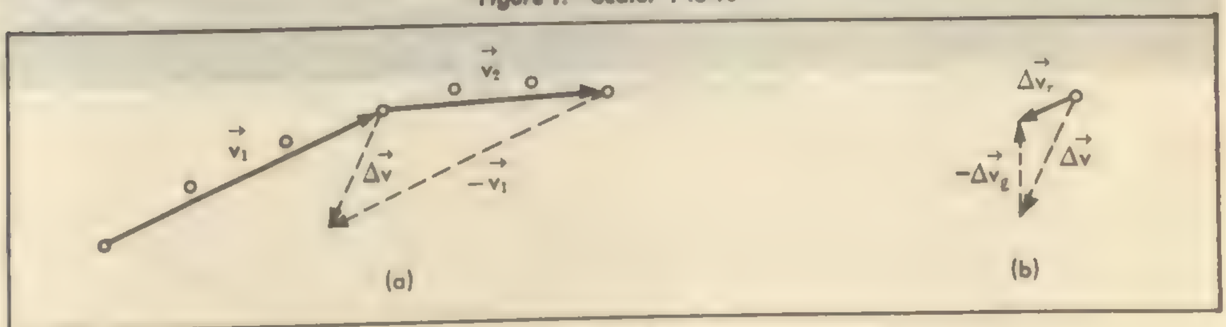


Figure 2

the velocity changes the same? What do you conclude about the direction of the resultant force on the ball?

What change in velocity of the ball in each 0.1 sec was caused by the force of gravity? In what direction did it act? Express this velocity change $\Delta\vec{v}_g$ in meters per *tenth* of a second and subtract it from each of the total velocity changes $\Delta\vec{v}$ on your diagram [Fig. 2 (b)]. The velocity change due to gravity must also be reduced to the scale of the photograph before you subtract it on your diagram. By using a ruler, you can see that the photograph is one tenth of its real size.

Do the residual velocity changes $\Delta\vec{v}_r$ all have the same magnitude? In what direction are they? Describe, qualitatively, the properties of the force that caused them. What do you think was responsible for the force?

What can you conclude about the mass of the projectile?

Plot on your diagram the path the ball in Fig. 1 would have followed if gravity had been the only force acting on it.

How do you explain the paths followed by the projectile in Figs. 3 and 4?

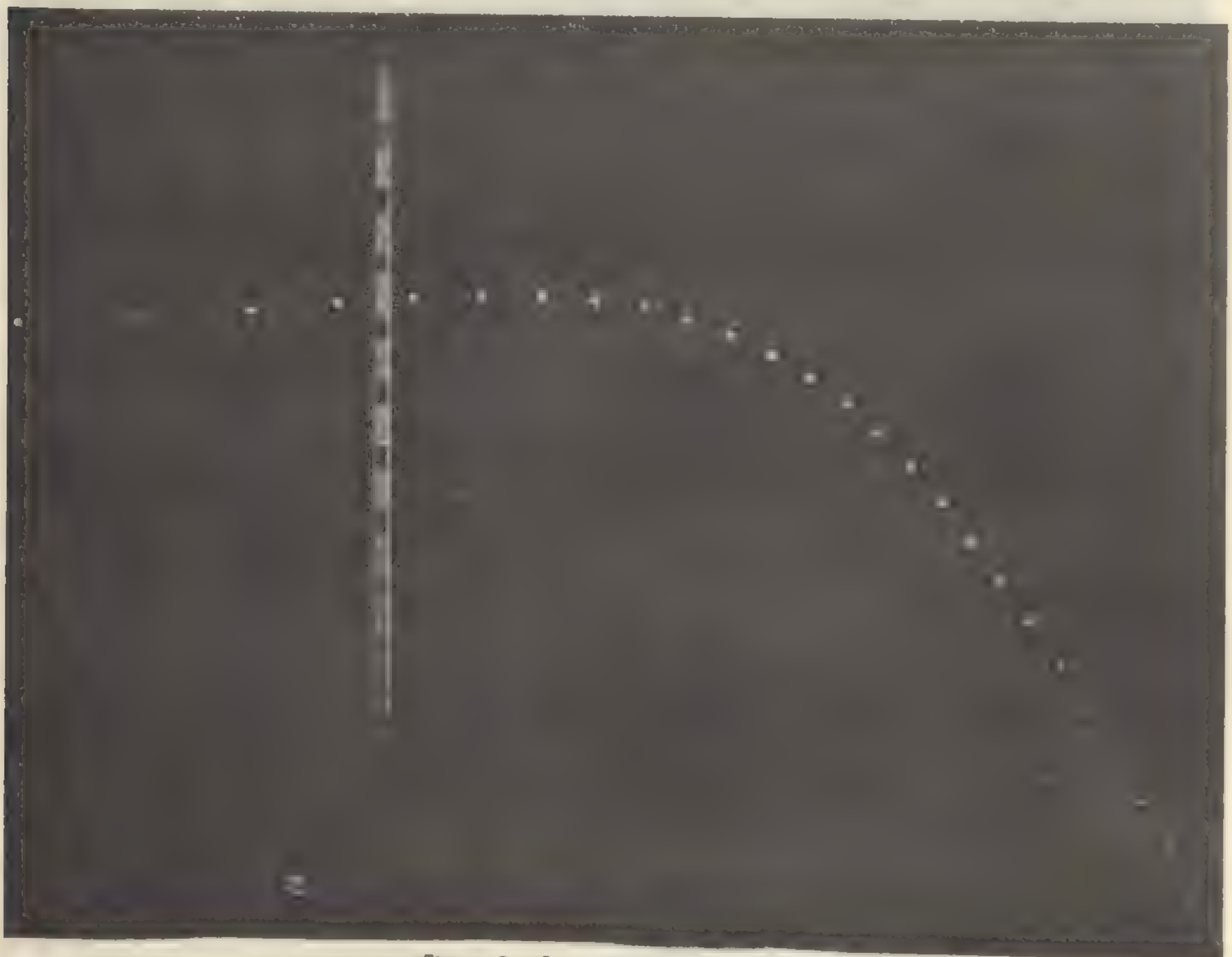


Figure 3. **Scale: Approx. 1 to 11.5**

Figure 4. Scale: Approx. 1 to 11.5

III-6. CENTRIPETAL FORCE

Motion in a circle at constant speed is an accelerated motion; although the magnitude of the velocity stays the same, the direction of the velocity vector is continuously changing. (Text, Section 6–6.) We know from Newton's law that a force is needed to maintain this acceleration. How is this force related to the object's speed, its mass, and the radius of the circle?

To answer these questions we shall use the simple apparatus shown in Fig. 1, which allows us to measure the force while observing the motion. When the glass tube is swung in a small circle above your head, the rubber stopper moves around in a horizontal circle at the end of a string which is threaded through the tube and fastened to some washers hanging below. The force of gravity on these washers, acting along the thread, provides the horizontal force needed to keep the stopper moving in a circle. This horizontal force is called the centripetal force.

With only one washer on the end of the string to keep the stopper from getting away, whirl the stopper over your head while holding onto the string below the tube. Do you have to increase the pull on the string when you increase the speed of the stopper? What happens if you let go of the string?

Now quantitatively investigate the dependence of the accelerating force on the speed, the mass, and the radius. First find out how the force depends on the speed, keeping the mass and the radius constant.

Pull enough string through the tube so the stopper will whirl in a circle of about 100 cm radius. Attach an alligator clip to the string just below the tube to serve as a marker so you can keep the radius constant while whirling the stopper. Hang six or more washers on the end of the string.

To find the rate of revolution of the stopper, have a partner measure the time while you swing the stopper around and count the number of revolutions. From the time and number of revolutions calculate the period and frequency $f = 1/T$. Repeat the experiment with larger numbers of washers.

Plot the period of the motion as a function of the number of washers. Can you think of a more useful way to plot your data? Try plotting the frequency instead of the period. Try f^2. What is the dependence of the centripetal force on the frequency when the revolving mass and the radius are kept constant?

To investigate the dependence of the centripetal force on the revolving mass, you could whirl two stoppers on the end of the string. What would you expect to find? On what do you base your prediction?

It is more difficult to investigate experimentally the dependence of the centripetal force on the radius when the frequency and mass remain constant. Can you suggest a way of doing this? What is the dependence of the centripetal force on the mass, the radius, and the frequency?

You will notice that as you swung the stopper around, the part of the string from the tube to the stopper was not quite horizontal. The gravitational force on the stopper pulled it down. Can you see why this effect of the gravitational force does not change the relation between the force (measured in number of washers), the length of the string from the tube to the stopper, and the frequency of revolution?

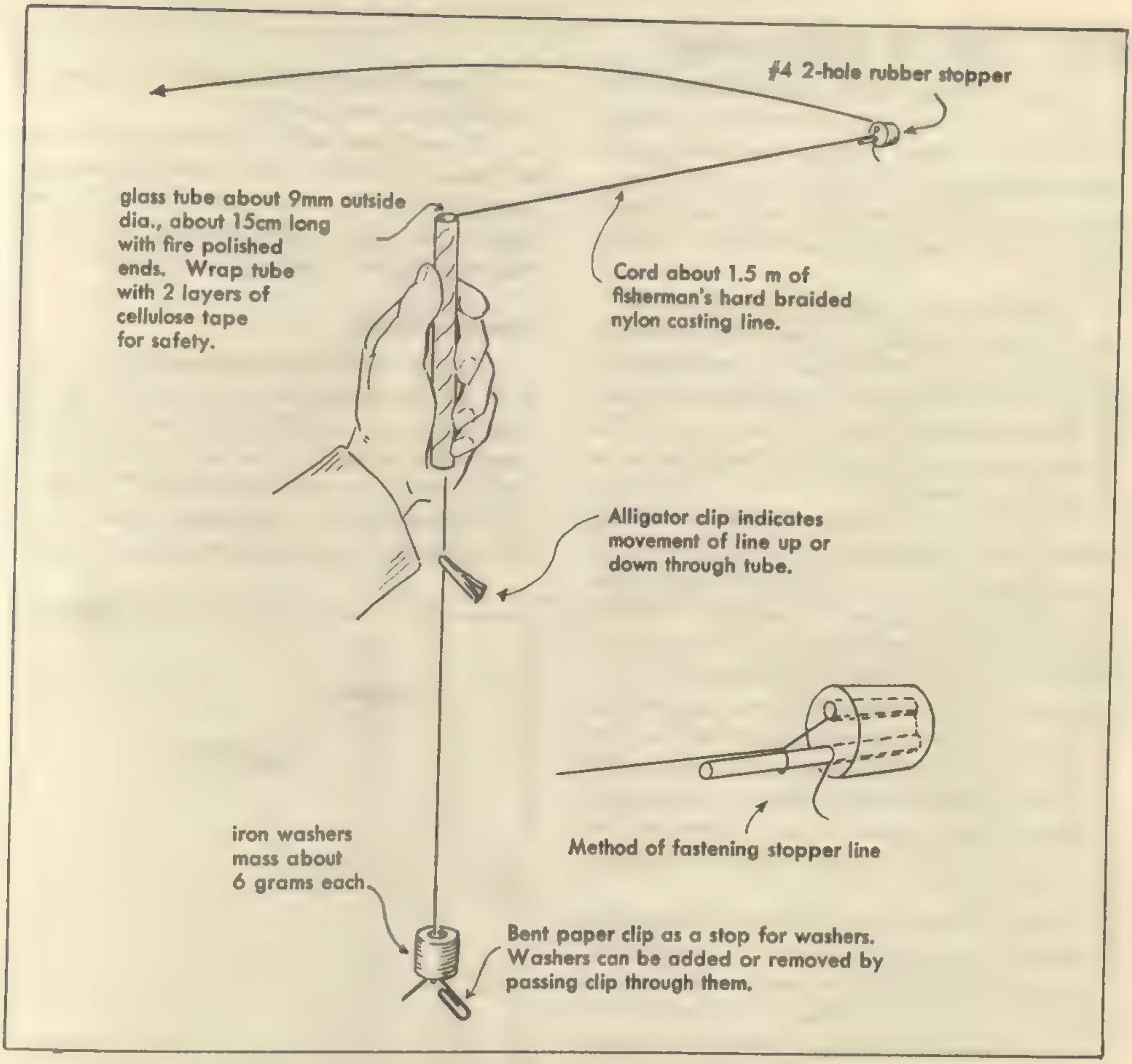

#4 2-hole rubber stopper
glass tube about 9mm outside dia., about 15cm long with fire polished ends. Wrap tube with 2 layers of cellulose tape for safety.
Cord about 1.5 m of fisherman's hard braided nylon casting line.
Alligator clip indicates movement of line up or down through tube.
Method of fastening stopper line
iron washers mass about 6 grams each
Bent paper clip as a stop for washers. Washers can be added or removed by passing clip through them.

Figure 1

III-7. LAW OF EQUAL AREAS

Kepler discovered that the planets follow elliptical paths and that an imaginary straight line from the sun to a planet would sweep out equal areas in equal time intervals. We cannot experiment with the planets, but we can experiment with a pendulum having an elliptical motion.

The bob of a pendulum swinging in a small arc moves back and forth along a nearly horizontal line. When such a pendulum is tapped sideward, the bob describes an ellipse. In this experiment you will find out if the pendulum bob also sweeps out equal areas in equal time intervals.

The bob is also our timing device. It is a conical paper cup filled with fine sand (or salt). A small hole in the bottom of the cup permits the sand to run out at a reasonably constant rate. When the cup swings in an ellipse at the end of a string with the sand running out of it, the mass of the sand deposited on any given arc of the ellipse will be proportional to the time it took the cup to pass over that arc. Each piece of paper placed along the path of the cup will therefore collect a mass of sand proportional to the time taken by the cup to pass over that paper (Fig. 1).

Place a large sheet of paper beneath the pendulum centered under the rest position of the pendulum. Mark the rest position on the paper. With the cup filled with sand and the hole in the bottom plugged, make several trial runs to get the approximate orbit before your final run. Now space small pieces of paper around the orbit as shown in the figure. With the hole unplugged start the pendulum on its orbit again. Why is it a good idea to let the cup make several complete trips?

Mark the pairs of points along the elliptical path where each small piece of paper is placed. Lines drawn from the center of the ellipse to a pair of points (A and B, Fig. 2) and the arc of the ellipse AB will enclose the area swept out by the bob as it moved along that arc.

Measured in terms of mass of sand, what are the times taken by the bob to cross each piece of paper? What is the area swept out by the bob in crossing each piece of paper? Are equal areas swept out in equal times by a line from the bob to the center of the ellipse?

Repeat the experiment with an ellipse of size different from the first.

Toward what point does the net force on the pendulum always act? How can you check your answer? In what respect does the net force on the bob resemble the force acting on a planet and in what respect does it differ?

Alternative Method

Take a multi-flash photograph of the bob as it swings through one revolution (Fig. 3). The camera is placed directly above the pendulum looking down and the motor-driven disc is placed directly in front of the lens. The bob is illuminated with two floodlights. Best results are obtained if the pendulum swings through a

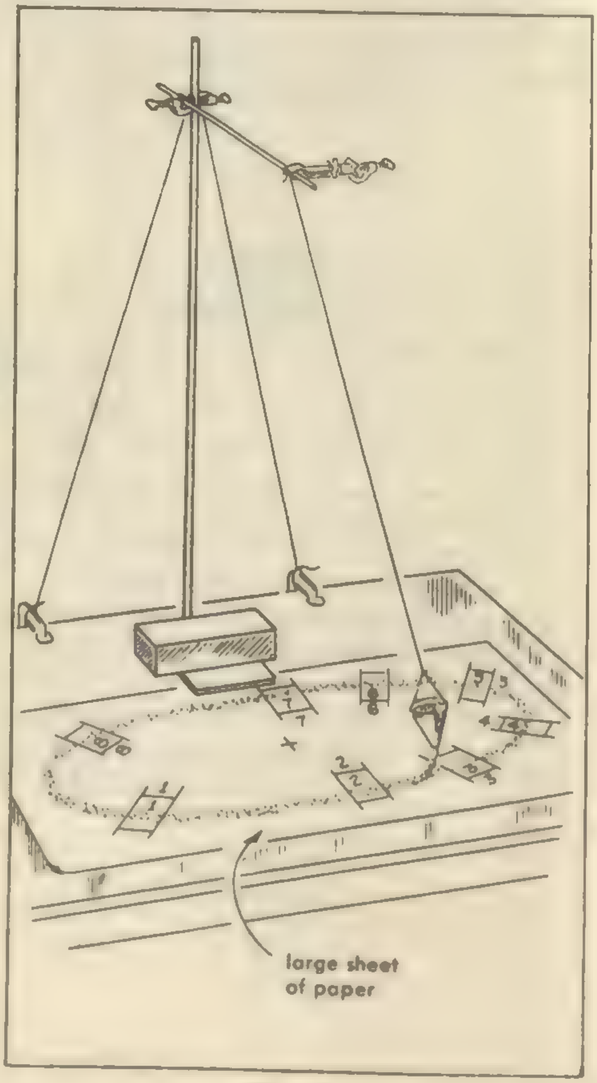


Figure 1

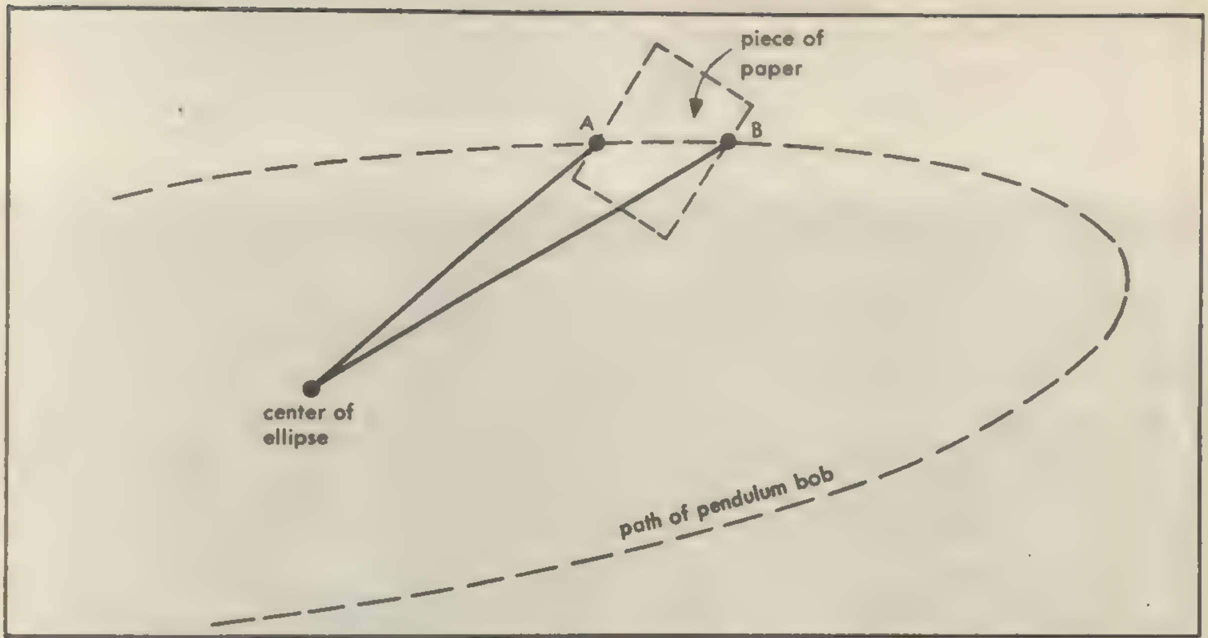


Figure 2

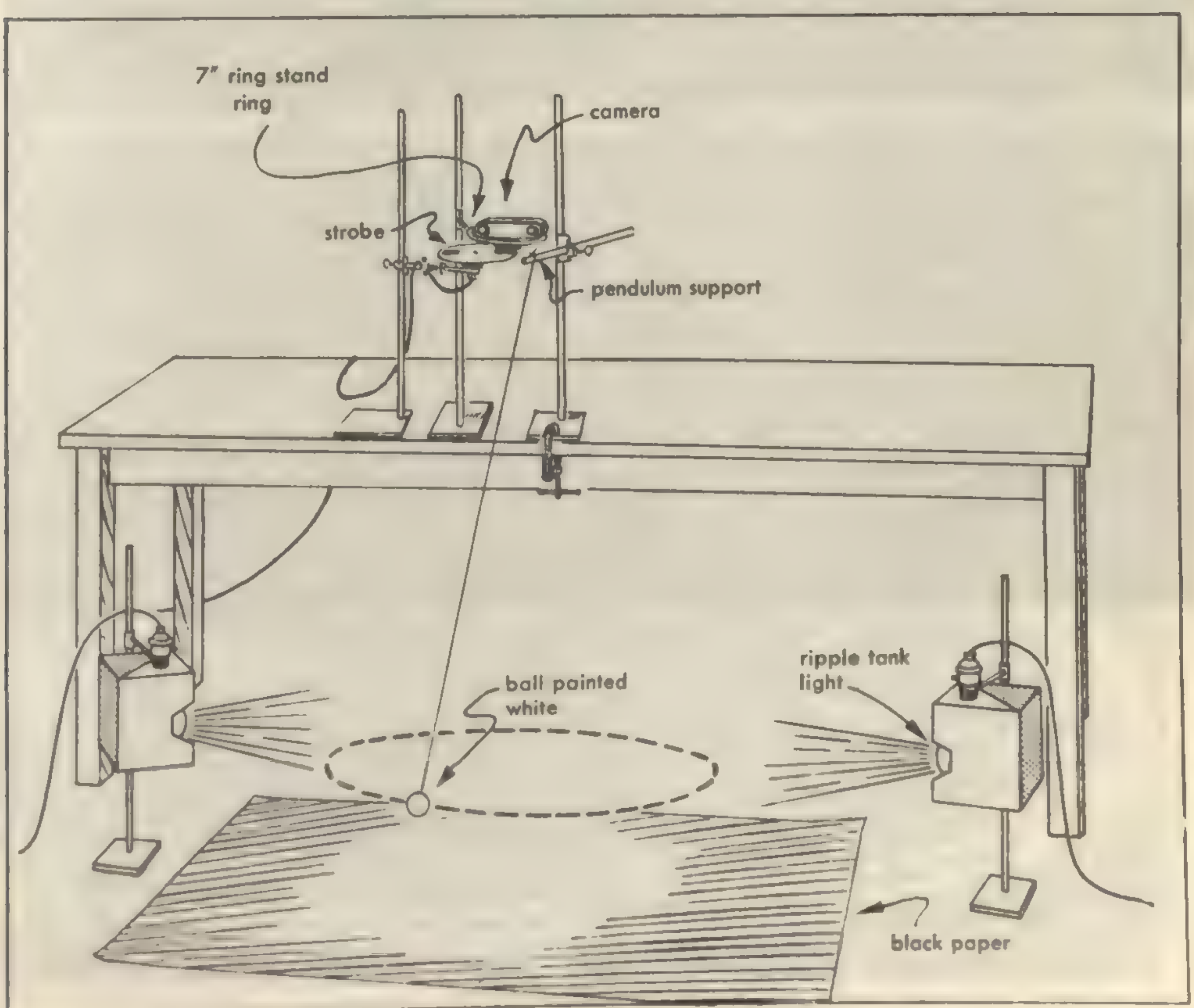


Figure 3

maximum vertical arc of 10 to 15 degrees. The longer the pendulum the larger the ellipse can be. If you do not have the necessary photographic equipment, analyze Figs. 5 and 6, which are photographs taken using the set-up shown in Fig. 3.

The analysis of these photographs is similar to that described in the previous section. Notice, however, that the time intervals between consecutive images are equal.

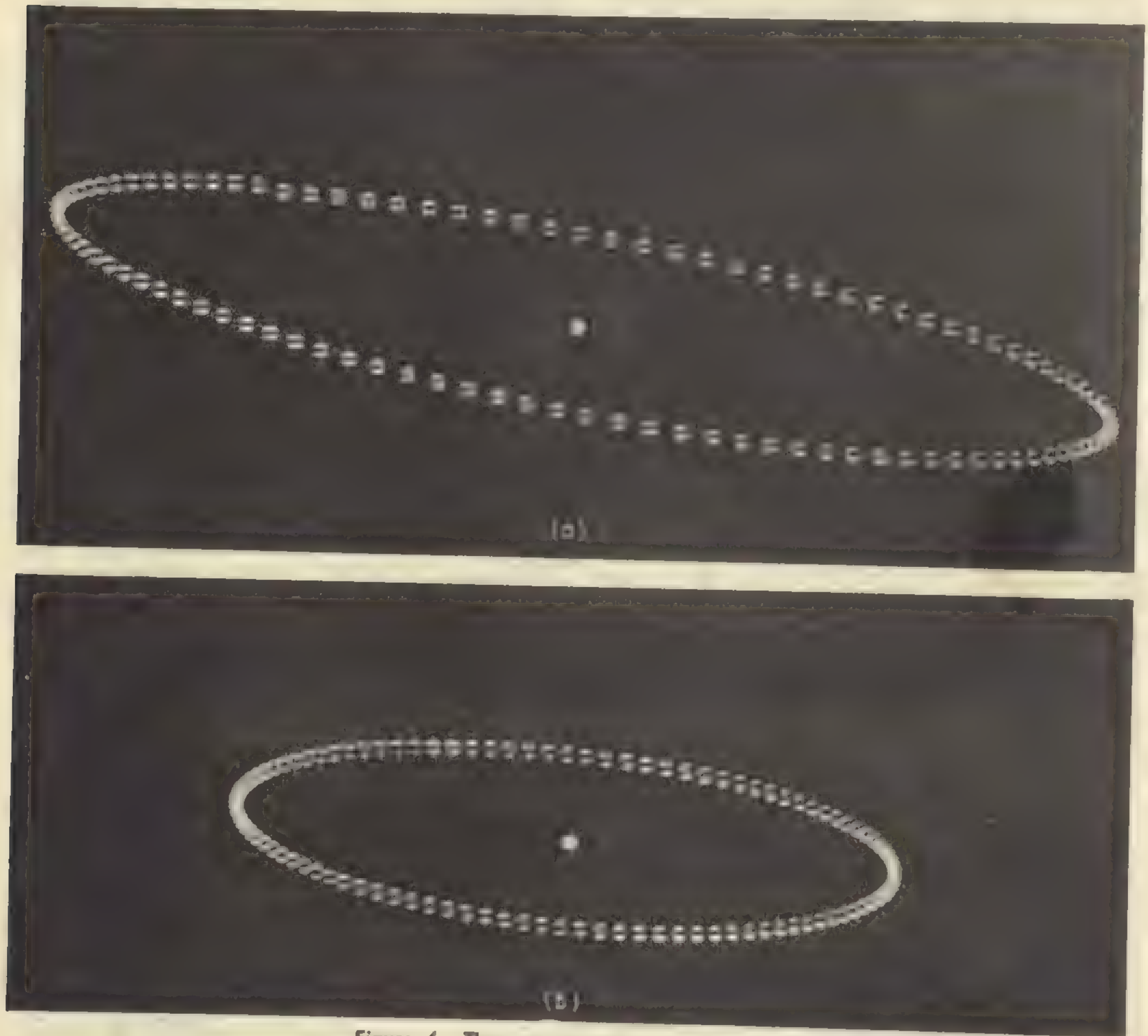


Figure 4. These photographs were taken at the same scale.

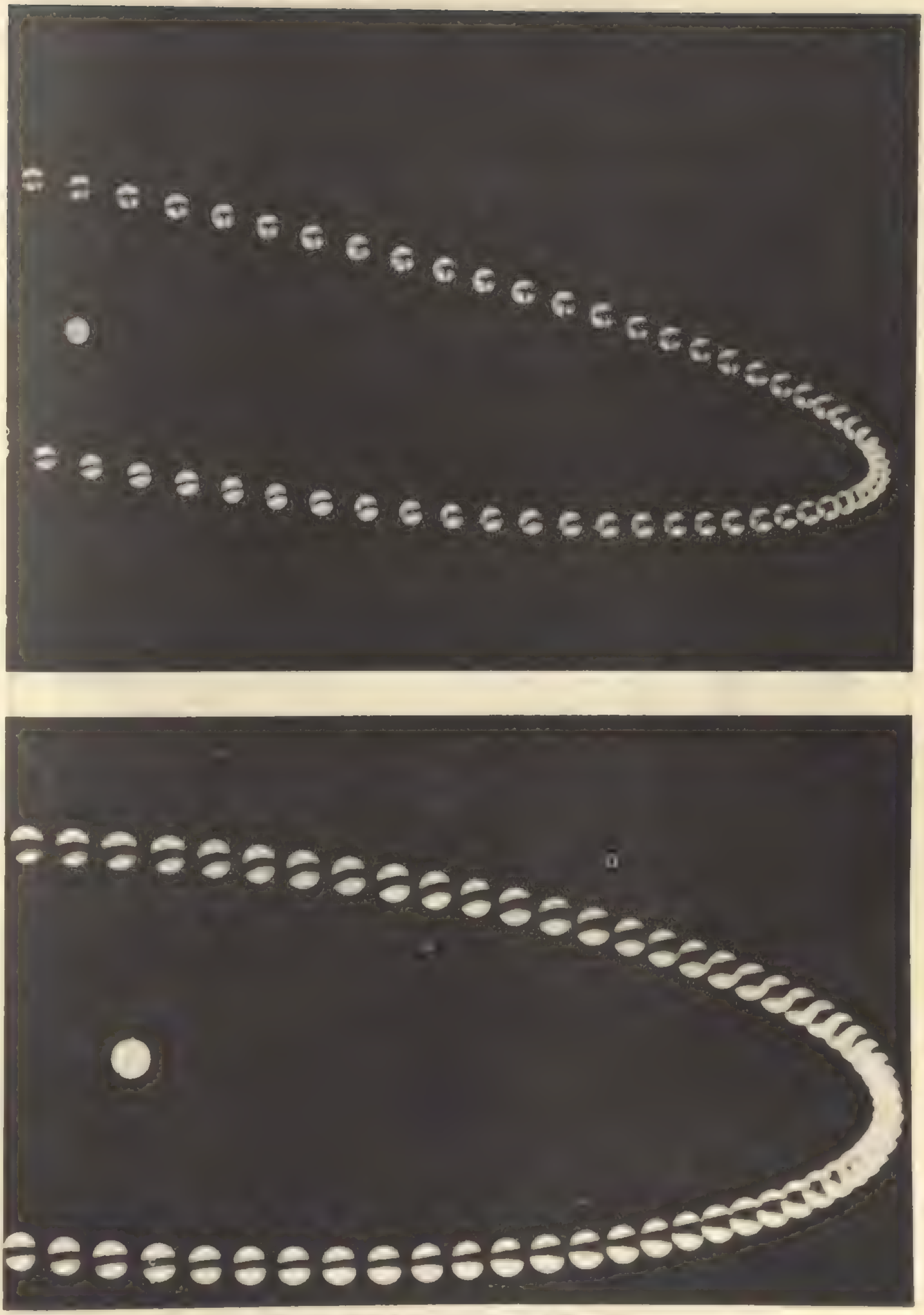


Figure 6. This is an enlargement of Fig. 4 (b).

III-8. MOMENTUM CHANGES IN AN EXPLOSION

Two carts are pushed apart from rest as the result of a sudden force—an "explosion"—acting between them. How do the momenta of the carts change?

To apply the sudden force we use a spring which we compress and suddenly release (Fig. 1). Release the spring with the cart at rest. What do you observe? Try this with different loads on the cart. What do you conclude about the horizontal component of the momentum of the cart before and after the explosion?

Place a second cart next to the first one so the spring will push against the second cart when released. What happens now as you release the spring? Do this experiment with various loads on the carts. Qualitatively, what would you say about the velocities of the two carts as you load them with different masses? How do you think the momenta of the two carts compare after the "explosion"?

To make this experiment quantitative we need to measure the velocities and the masses of the two carts. But we do not have to know their velocities in meters per second; any unit will do. It is possible to find their velocities in terms of the distances both carts move during the same time interval. Suppose we release the carts just halfway between two wooden bumpers and they go at the same speed. We will hear just one sound as they hit the bumpers at the same time. If one goes faster than the other, it will hit earlier and we will hear two distinct

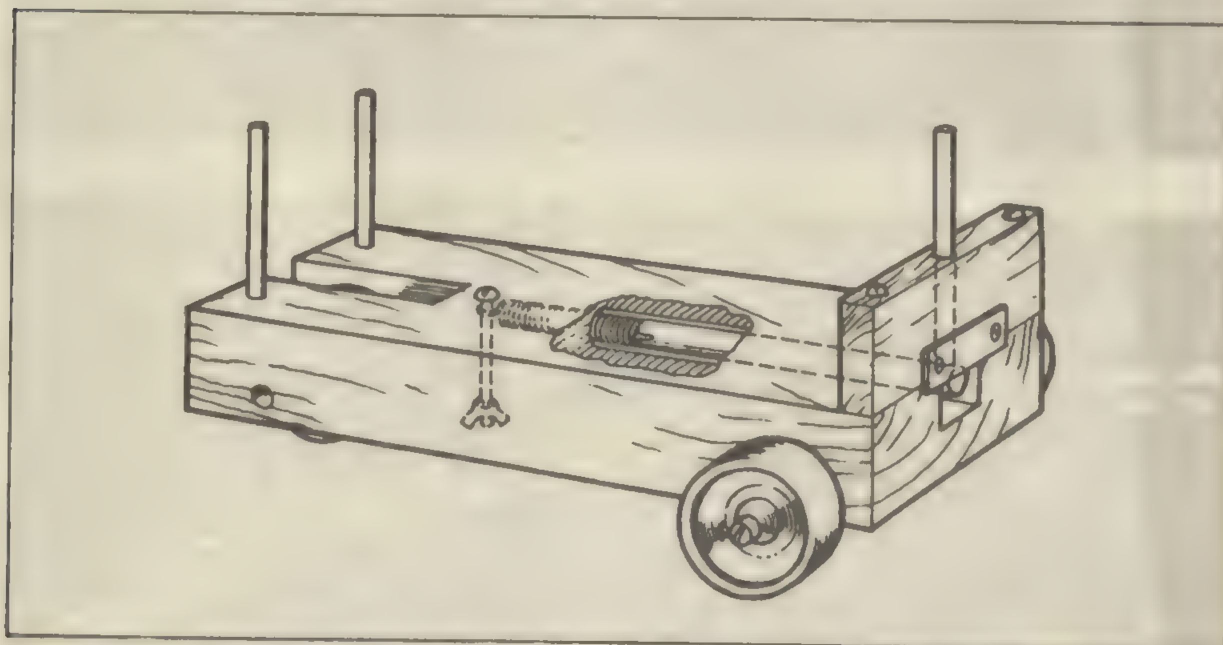


Figure 1. To load the exploder, push the dowel inside the tube and pass it up behind the metal plate. To release the exploder, tap the vertical dowel at the front.

sounds instead of one. We can, however, move the starting point so the faster cart has to travel a longer distance before hitting the bumper. After several trials we can find a position from which both carts will take the same time to travel to the bumpers. The distance traveled by the carts from rest positions are shown as x_1 and x_2 in Fig. 2. The carts travel these distances in the same time interval t and, if they move at constant velocity, we can write for their velocities:

$$v_1 = \frac{x_1}{t}; \quad v_2 = \frac{x_2}{t}$$

and

$$\frac{v_1}{v_2} = \frac{x_1}{x_2}.$$

The velocities, therefore, are proportional to the distances moved in the same time interval.

Using this method of moving the starting point to give equal times, determine the ratio of the momenta of your carts after explosion. What is the change in momentum of each cart as a result of the explosion? Try this with different combinations of masses on the cart. Can you draw any conclusions concerning the total momentum of the system after the explosion compared with the total momentum before the explosion?

What would happen to the total momentum of your carts if, instead of the spring, you placed a stick of dynamite between them and blew pieces of the carts in all directions? (Don't do it!)

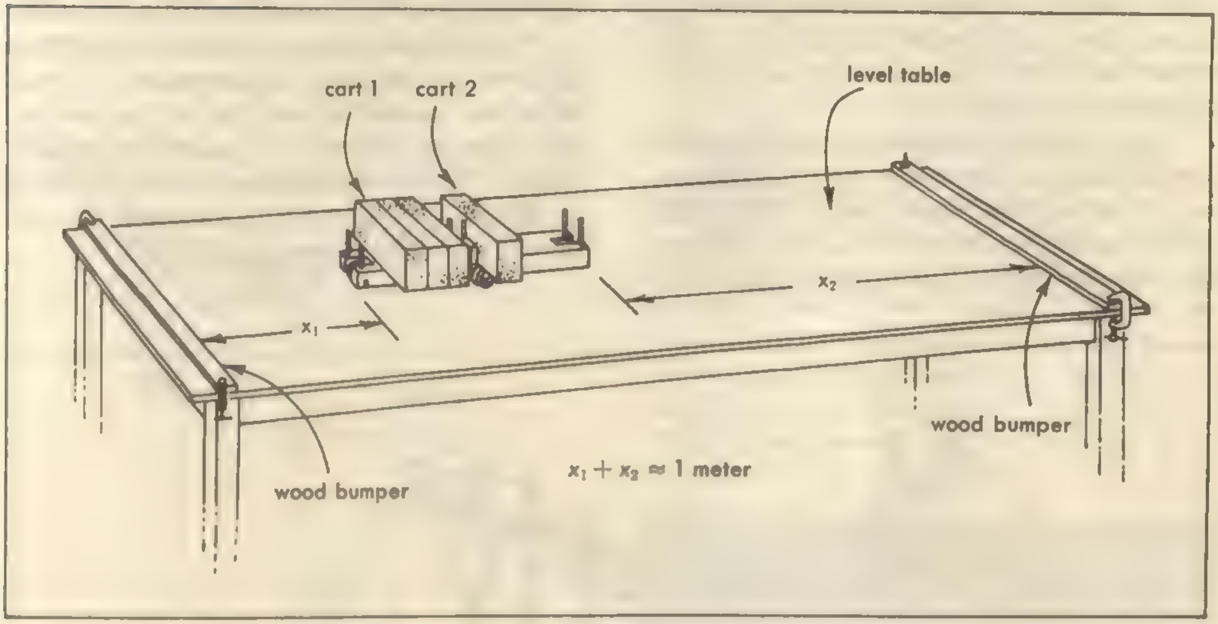


Figure 2

III-9. *THE CART AND THE BRICK*

What happens when a suspended brick is dropped on a moving cart as the cart passes beneath the brick? Suspend a brick so the cart can just pass beneath without touching it (Fig. 1). The hanging brick should be horizontal and motionless. Move the cart back, give it a push, and release the brick as the cart passes beneath it. What happens? Try the experiment again with the cart loaded with different numbers of bricks. What is the effect of increasing the mass of the cart by loading it with bricks?

To make accurate measurements, record the motion for both loaded and unloaded carts. Since you wish to have the motion as uniform as possible before and after the brick collides with the cart, start the cart with a reasonably high speed.

From the tapes and the masses of the cart and the brick, compute the change in momentum of the cart and the change in horizontal momentum of the brick. You can compute the momenta in units of kilogram-meters per "tick." How do they compare? What is the total horizontal momentum of cart and brick before and after they interact? Is momentum conserved?

What is the horizontal impulse applied to the falling brick? Try to estimate the length of time of the interaction by examining your tapes. Can you make a rough estimate of the horizontal force applied to the falling brick? How does this compare with the force the brick applied to the cart?

What happened to the vertical momentum of the brick? Would it make any difference if the brick were dropped from different heights as long as you didn't break the cart or the table?

What would happen if, instead of dropping the brick on the cart, you suspended a funnel full of sand above the table and let the sand run into a box on the cart as it passed beneath the funnel? What would happen to the velocity of the cart if, instead of letting the sand run into the cart, you let the sand run out of it?

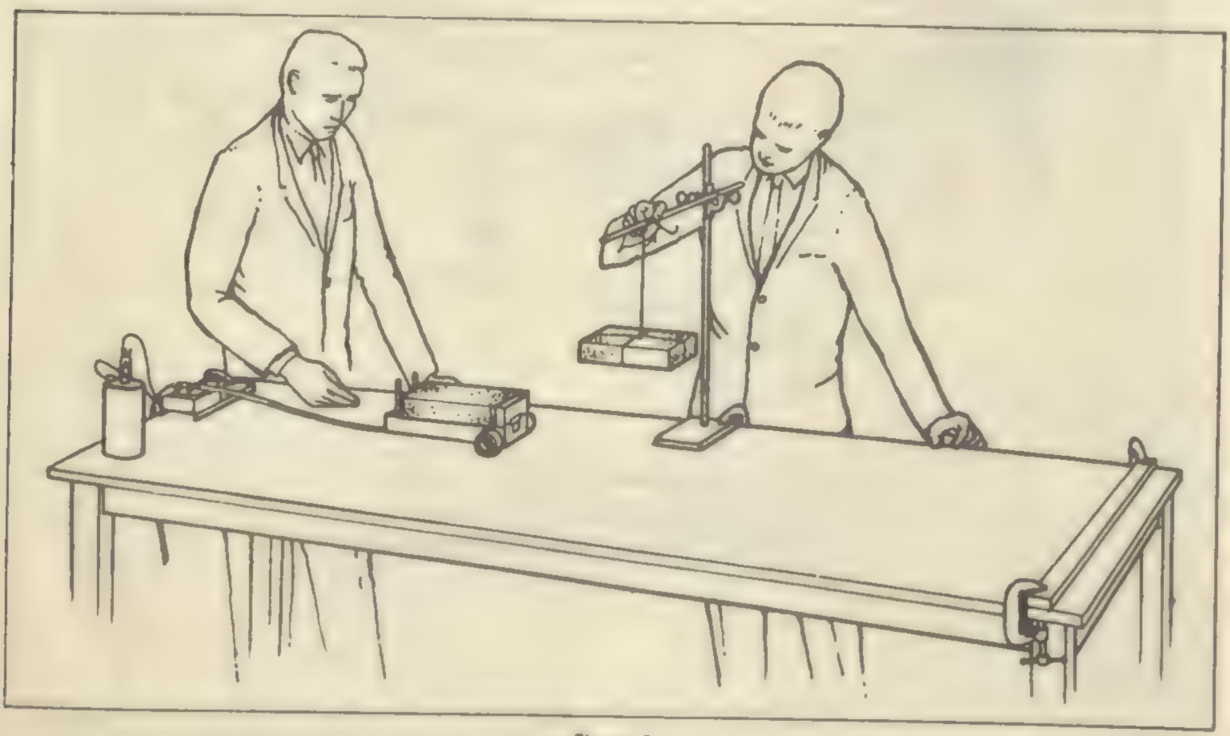


Figure 1

III-10. *A COLLISION IN TWO DIMENSIONS*

Previously we investigated the momenta of colliding bodies moving along a single straight line. What happens when two bodies go off in different directions after colliding? To find out, we shall roll one steel ball down an incline so it makes a glancing collision with another steel ball of the same size, knocking it off a support near the edge of the table (Fig. 1). We will then find the momenta of each from their masses and velocities.

To find the velocities of the spheres, we shall use what we have learned about projectile motion (see text, Section 21–3). We know that objects projected with different horizontal velocities from the edge of a table take the same time to fall to the floor. Neglecting air resistance, the horizontal component of their velocity remains unchanged and therefore the distance they go horizontally is proportional to their horizontal velocity. We can use this fact to measure the velocities of the spheres after they have collided.

To give an initial velocity to one of the spheres, roll it down the grooved ruler (Fig. 2). The target sphere rests in the slight depression on the top of the set screw. Place the set screw directly in the path of the incident sphere at a distance of one radius from the end of the ruler. Adjust the height of the set screw so the incident sphere will just clear its top when rolled down the incline from a point up the ruler (25 cm is a good choice).

Now find the point on the floor directly below the screw, using the plumb line.

Tape four sheets of onionskin or tracing paper together to make a single large sheet. Be sure the sheets do not overlap. Do the same with four sheets of carbon paper. Adjust the carbon paper, carbon side up, on the floor with the tracing paper on top of it; the plumb bob should hang directly over the middle of the shorter side (Fig. 1). Mark this point on the

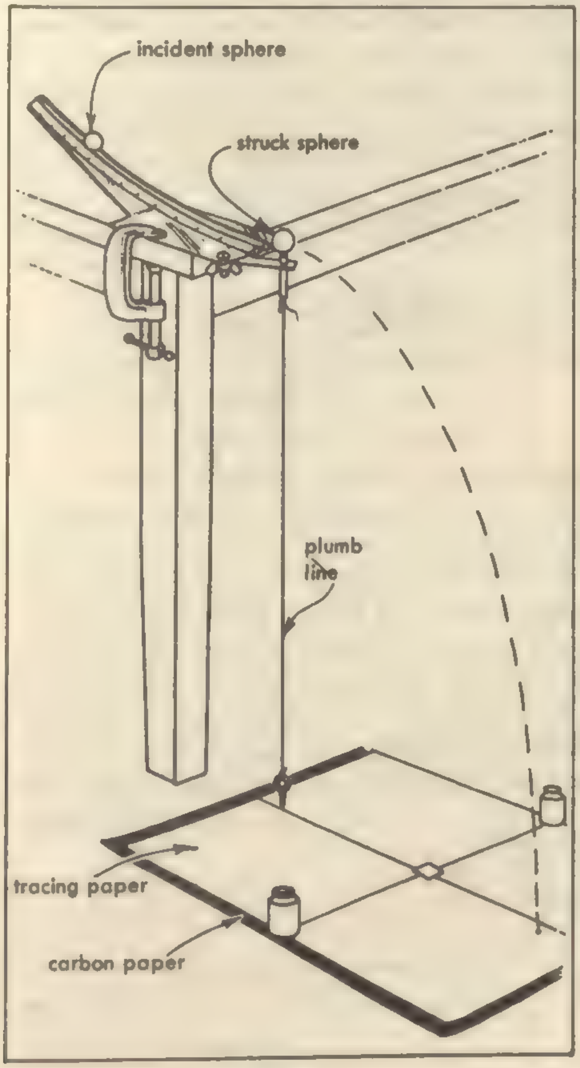


Figure 1

Figure 2

paper and weight the paper to hold it in place. Release a steel ball 25 cm from the lower end of the ruler ten or fifteen times and circle the distribution of points on the paper. To what degree is the initial velocity always the same?

If we now put the target sphere on the screw and roll another sphere down the incline, the collisions will take place before the incident sphere is over the screw. The incident sphere, slowed by the collision, will then bounce off the edge of the ramp. To prevent this, we must place the target sphere farther from the ramp. How far depends on how off-center the collision is. For a head-on collision, the screw supporting the target sphere should be 3 radii from the ramp [Fig. 3(a)] and at the height to which you adjusted it earlier. (Can you see why?) For a glancing collision, the screw should be at a distance just slightly greater than one radius from the ramp [Fig. 3(b)]. Such collisions are rare and therefore as a compromise we put the screw about 2.5 radii from the ramp [Fig. 3(c)].

Mark the point on the paper directly below this new position of the screw. With a steel ball balanced on the screw, try several collisions, releasing the incident ball from the same point as before on the ruler. To change the point of collision move the screw a small distance parallel to the edge of the ramp. A numbered circle around each impact on the paper and each starting point of the target ball will help you identify the different marks on the paper.

Draw on the paper the vectors that represent the velocities of the balls after collision.

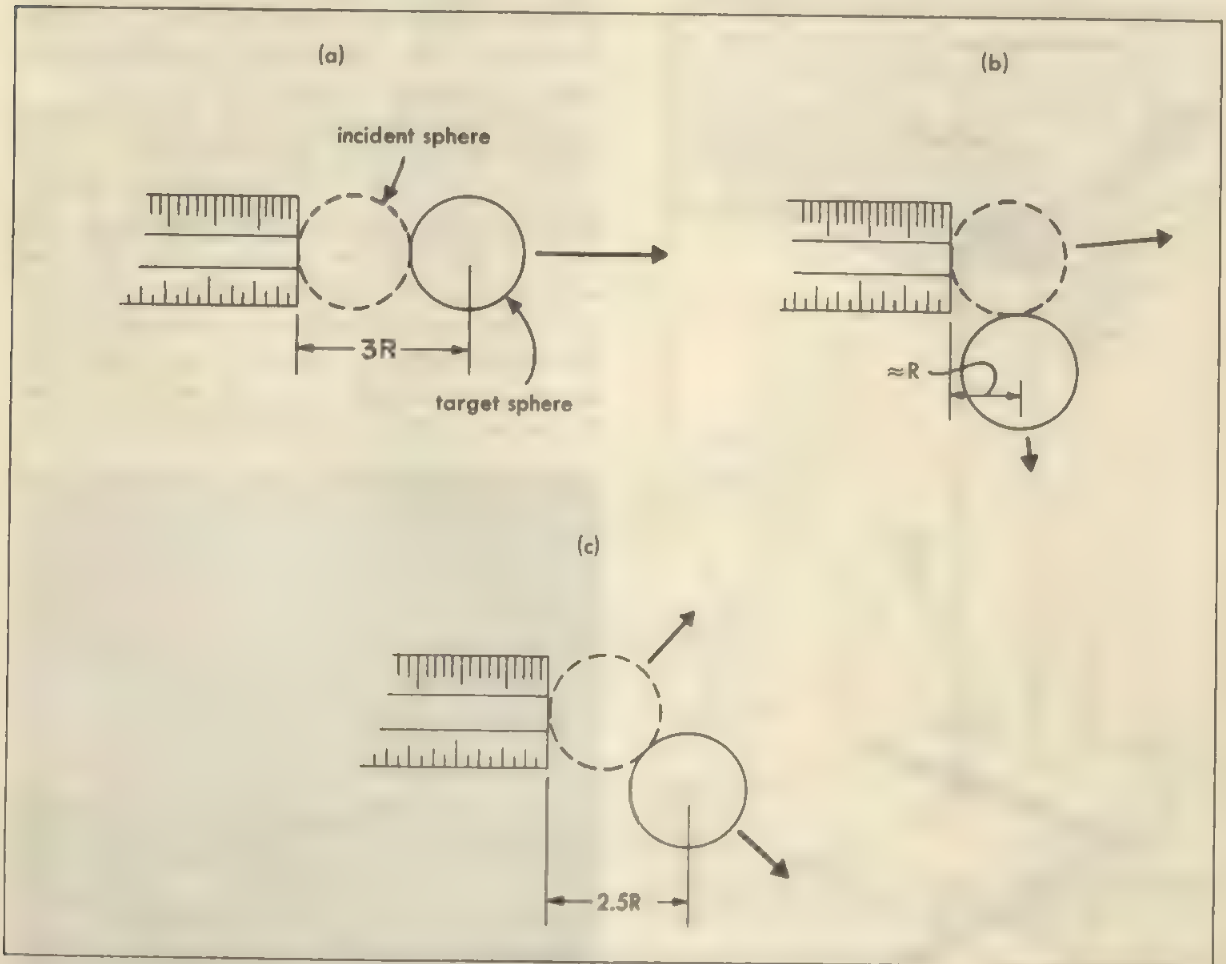


Figure 3

The position of the incident ball at the instant of impact can be determined with the help of Fig. 4.

Since the masses of the balls are equal, the velocity vectors represent the momenta of the balls. Add the two momentum vectors graphically on your paper, placing the tail of the momentum vector of the target ball at the head of the momentum vector of the incident ball.

How does the vector sum of the two final momenta compare with the initial momentum of the incident ball? Is momentum conserved in these interactions? How does the arithmetic sum of the two magnitudes of the momenta after collision compare with the magnitude of the initial momentum of the incident ball?

Repeat the experiment using two spheres of unequal mass but of the same size. Which one should you use as the incident sphere? How does the vector sum of the final velocities compare with the initial velocity? How can you convert the velocity vectors to momentum vectors now that the masses of the two spheres are not equal? How does the vector sum of the final momenta compare with the initial momentum?

Compare the vector components of the final momenta of the two balls in a direction at right angles to the initial momentum. What do you find?

For each collision involving equal masses, calculate the *square* of the velocities before and after collision. How do they compare? Does this suggest that something else is conserved besides momentum? Make the same calculations for the unequal mass collisions. Is the square of the velocities conserved? For unequal masses, multiply the squares of the velocities by the respective masses and compare the values you obtain. What else do you think is conserved besides the momenta?

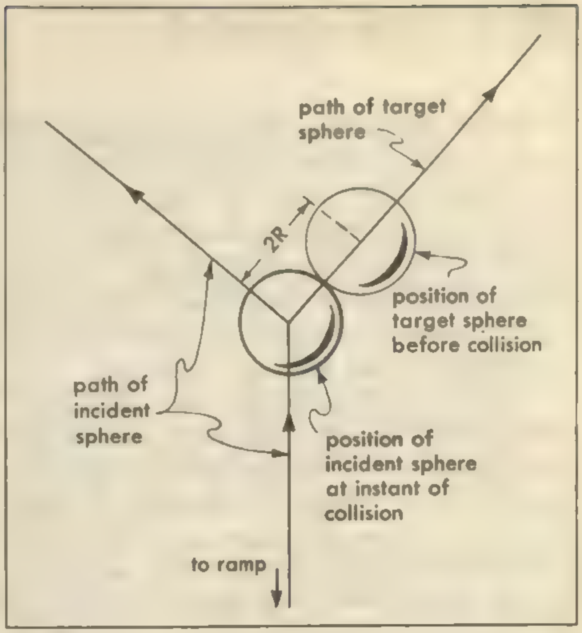


Figure 4

III-11. SLOW COLLISIONS

In the previous collision experiments, the duration of the collisions was so short that you were unable to examine in detail how the velocities changed during the collisions. You could analyze only the final changes. In this experiment you will qualitatively study very slow collisions between two carts and find out what happens while they are interacting.

You will use two loaded carts with "soft" spring bumpers (Fig. 1) and examine an interaction similar to that described in the text (Section 24–5). There the interaction force was zero when the separation was greater than a distance d and constant when the separation was less than d. With the spring bumpers on the carts, the interaction begins when the bumpers make contact and the carts are separated by the distance d (Fig. 2). As the carts get closer together during the interaction the force increases, unlike the constant force described in the text. The over-all results, however, are very much the same, although a careful mathematical analysis of the interaction would be difficult. Using the two carts try to duplicate qualitatively, as closely as you can, the interaction described in the text (Section 24–5) making the interaction as slow as possible. Put three bricks on the incident cart and one on the stationary cart to approximate the mass ratio of the example in the text.

Is kinetic energy lost by the incident cart and gained by the struck cart during the interaction? What can you say about the total kinetic energy when the carts are at minimum separation? How do the velocities of the two carts compare at their minimum separation?

What happens in collisions when the carts are equally loaded?

How are the interaction time and distance of minimum separations affected by (a) changing the total mass on the carts and (b) changing the velocity of the incident cart?

Try collisions with loaded carts when both are initially in motion.

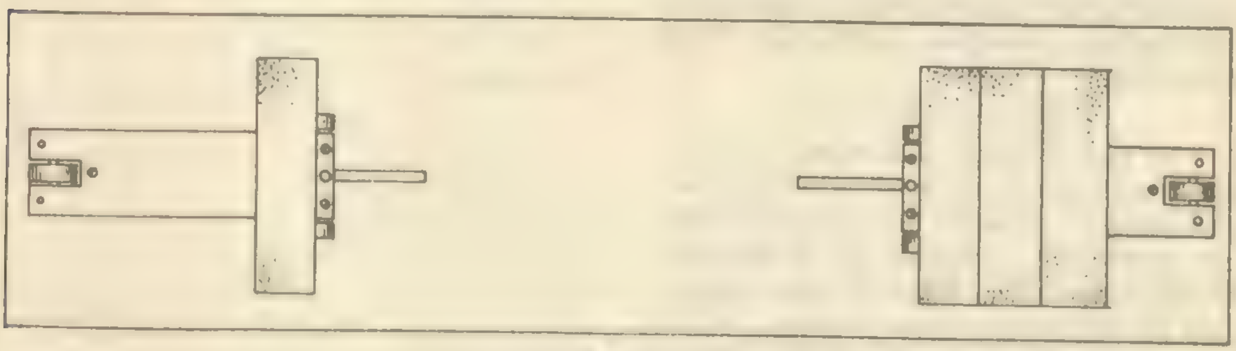


Figure 1

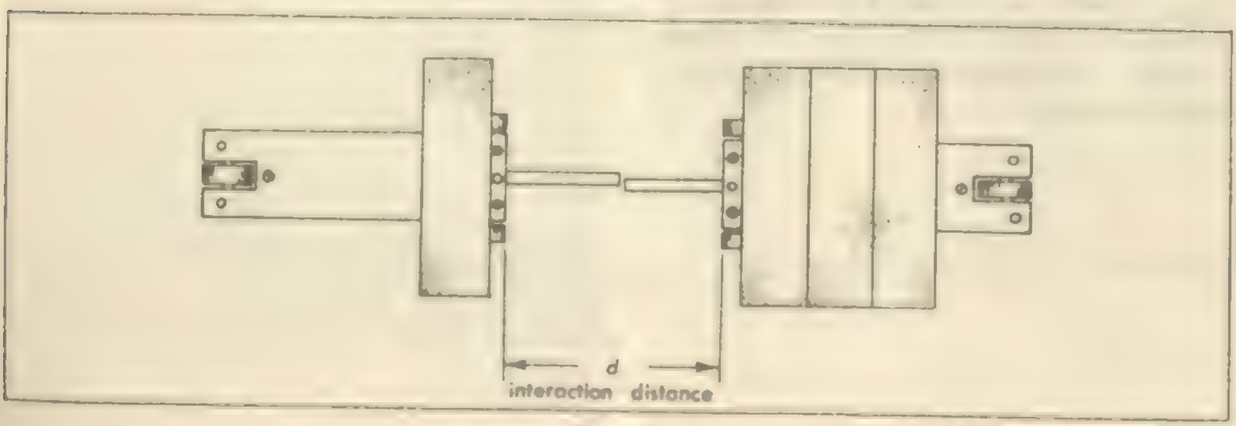


Figure 2

III-12. *CHANGES IN POTENTIAL ENERGY*

Hang a spring from a ringstand and attach a mass of about one kilogram to it. Lift the mass a few centimeters above its rest position and let it fall. At the top and bottom of its motion it is at rest. When the mass is at the bottom of its motion, its energy is stored in the spring. At the top of its motion its energy is stored in the gravitational field. Compare the change in gravitational energy with the change in potential energy stored in the spring.

You can find the change in potential energy of the spring when it is stretched a distance Δx from x_1 to x_2 by calculating the work done in stretching it from x_1 to x_2 (Fig. 1). The change in gravitational potential energy when the mass falls this same distance Δx can be found by calculating the work done in lifting the mass through the distance Δx. You can then compare the gravitational energy lost as the mass falls from rest to its lowest point with the spring energy gained as the spring stretches.

To find the potential energy of the spring, we first find how the extension x of the spring is related to the force that stretches it. Hang known masses up to a maximum of about 1.5 kg on the end of the spring and find the extension x in meters as a function of the force F in newtons. Plot a graph of x as a function of F. Is F proportional to x for this spring in the range of your measurements?

If your graph is a straight line, find the spring constant $k = \frac{F}{x}$ from the slope and write down the potential energy function of the spring, that is, the equation for the energy stored in the spring as a function of the extension of the spring. How can you find the potential energy stored in the spring for a given extension if your graph is not a straight line?

Now hang a one-kilogram mass on the spring and support it with your hand so the spring extends about 20 cm more than its natural length when hanging without the mass. Use clothespins clamped to the ringstand to mark the lower end of the unloaded spring and the point from which you drop the mass. Release the mass and note how far it falls. Place a clothespin on the stand to mark the lowest point of the fall. Release the mass several times until you have accurately located the lowest point of the vibration.

Calculate the loss in gravitational potential energy and the gain in potential energy of the spring when the mass falls. How do they compare? Repeat the above experiment, releasing the mass from a point about 25 cm from the lower end of the unloaded spring. Repeat the experiment with a 0.5 kg mass and calculate the change in gravitational potential energy and spring potential energy when the mass falls from a point about 10 cm below the end of the unloaded spring.

Is energy conserved in these interactions between the masses and the spring? Are they elastic interactions?

What is the sum of the two potential energies when the kilogram mass has reached the halfway mark in its fall? How does this compare with the initial energy of the mass? How do you explain this? How could you check your explanation?

If you have time, plot a graph of the sum of the two potential energies as a function of the spring extension. What can you learn from this graph?

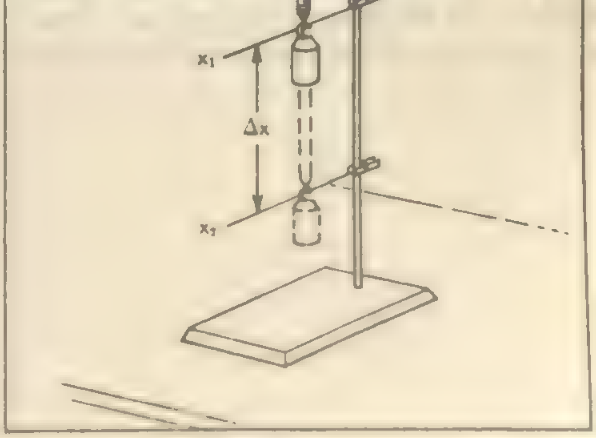


Figure 1

III–13. *THE ENERGY OF A SIMPLE PENDULUM*

In a swinging pendulum, kinetic energy is transferred to potential energy and vice versa. We can investigate this transfer by using a timing tape attached to a pendulum bob to measure the speed of the pendulum at different positions during its swing. To compare the kinetic energy and potential energy, we should be careful to express them in the same units—for example, in joules.

Hang a heavy bob, such as a brick, by a long string from a rigid support. The pendulum should be at least 2 meters long. Measure the length of the pendulum from the point of support to the center of the bob. Place a timer at about the level of the bob in its lowest position (Fig. 1). Pull the bob aside not more than 15° from the vertical and hold it in this position with a thread so the line of action of the pull of the thread passes through the center of gravity of the bob.

Start your timer and let go of the thread. The bob will swing through its arc, pulling the tape and making a record of the bob's position at successive time intervals. (Have your partner catch the bob just *after* it starts back at the end of its first swing.)

From the data recorded on the tape and from a calibration of the timer in seconds, plot a graph of the distance traveled by the bob as a function of time, measuring the distance from the point of release of the pendulum.

Using the data from your graph, find the velocity of the bob for at least eight different positions. Once you know the velocity and the mass of the bob you can compute the kinetic energy of the pendulum at any position. (What are the energy units if you use the brick as the unit of mass? What are they if you measure the mass of the brick in kilograms?) Plot a graph of the kinetic energy of the pendulum as a function of position. At which point is the kinetic energy a minimum? A maximum?

How does the potential energy change with the position of the bob? To find out, we need to know the heights through which the bob has been lifted. There is a simple relationship between the horizontal distance the bob travels and the height through which it is lifted. Calling L the length of the pendulum, x its horizontal displacement from the rest position, and h its height above the rest position, you can show that $h = x^2/2L$ as long as x is small compared with L. (See the remarks on the lensmaker's formula, text page 302.) What is the potential energy of the pendulum at the positions at which you calculated the kinetic energy? Plot the potential energy on the same graph on which you plotted the kinetic energy.

How does the potential-energy change compare with the kinetic-energy change? On your graph, plot the sum of the potential and kinetic energies. Are you sure you used the same units for both? What conclusion do you draw concerning the sum of the potential and kinetic energies of the pendulum?

Why did we limit the swing of the pendulum to 15° or less from the vertical? Could you do the experiment with a larger swing? How would you determine the potential energy in this case? Do you expect the sum of the two energies in this case to be constant?

Why was it unnecessary to measure the mass of the bob in order to compare the kinetic and potential energies?

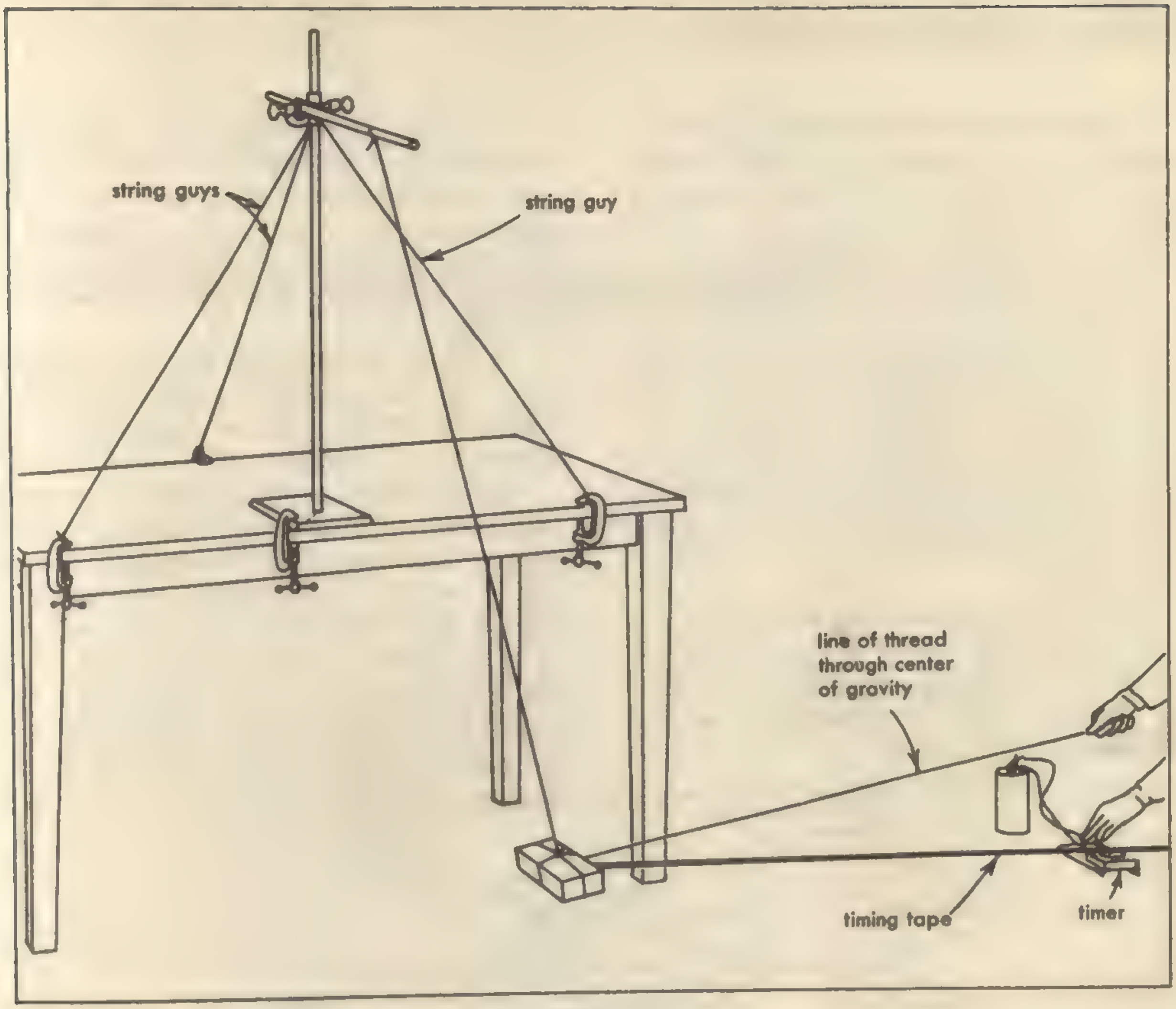

string guys
string guy
line of thread
through center
of gravity
timing tape
timer

Figure 1

III-14. A HEAD-ON COLLISION

The purpose of this experiment is to investigate the momenta and kinetic energy changes resulting from a collision between a moving cart and a stationary cart. Fig. 1 shows the arrangement of the apparatus.

Place the stationary cart near the middle of the table so both carts can move far enough to give accurate measurements of their velocities before and after the collision. Make timing tapes with several different combinations of masses on the carts but always have at least one brick on the lighter cart. Why is it necessary to have the mass on the cart initially in motion equal to or larger than the mass on the stationary cart?

Plot a graph of the velocity of each cart as a function of time. From this graph, what are the velocities of the cart just before and after the collision. Also from the graph, can you estimate the collision time?

Now find the momentum of each cart before and after the collision. How does the sum of the momenta of the carts before the collision compare with the sum of their momenta after the collision. What do you conclude? In what units have you expressed the momenta?

Calculate the kinetic energy of the carts before and after collision. Is kinetic energy conserved? What could be responsible for losses in kinetic energy?

If you have time, repeat the experiment with the spring bumper removed and a soft material like a blackboard eraser taped to the front of one cart. Make timing tapes and compute the momentum and energy of the system before and after collision. What do your results indicate concerning the conservation of momentum? Concerning the conservation of kinetic energy?

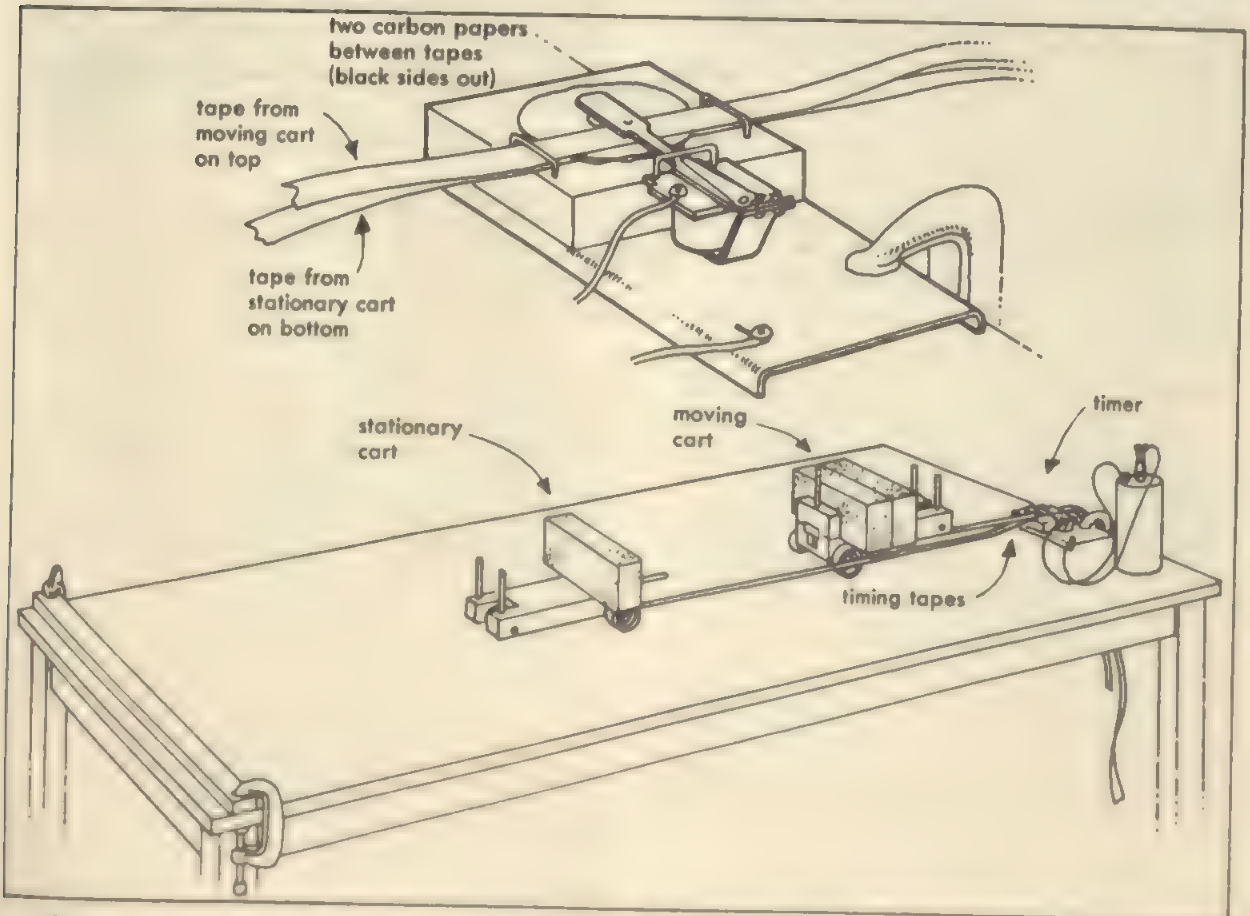


Figure 1. To use one timer for both carts, use two carbon-paper discs with the inked surface outside. The tape attached to the initially moving cart should be on top.

LABORATORY GUIDE

PART IV

IV-1. *ELECTRIFIED OBJECTS*

Much of the qualitative behavior of electric charges was discovered during the eighteenth century. Common materials like glass were rubbed with different kinds of cloth to produce electric charges. You can discover for yourself the behavior of electric charges by rubbing easily charged plastic strips with wool and cotton.

Hang a strip of cellulose acetate and a strip of vinylite by short lengths of masking tape from a crossbar of a ringstand so they can swing freely without twisting. Briskly rub the vinylite strip with a dry woolen cloth and the acetate strip with a dry cotton cloth. Do not touch the rubbed surfaces. Rub another vinylite strip with wool and bring it near each of the suspended strips. What do you conclude from the results?

Now rub another strip of acetate with cotton and bring it near the hanging strips. What do you infer?

Recharge the hanging vinylite strip by rubbing it with the wool. Stretch the wool by grasping it at both ends and hold it near the vinylite. What do you conclude?

Have you found one, two, or three kinds of charge? Assign names to each kind of charge you have found and use these names throughout the rest of the experiment.

Rub a comb, plastic ruler, or other substance that charges easily on your clothes and observe its effect on the two suspended pieces of plastic. Which kind of charge does the substance have?

What general conclusions about the electrification of bodies can you make as a result of your observations in this experiment?

What would be the result of changing the names you have given to the charges you observed?

What happens when you hold a charged strip close to a tiny piece of uncharged paper or thread?

IV-2. ELECTROSTATIC INDUCTION

You know from everyday experience that electric charges do not flow easily in materials such as glass, ceramics, and plastics. These are called insulators. Other materials, mostly metals, in which electric charges move easily, are called conductors. In this experiment you will investigate the consequences of the free motion of charges in a conductor.

Place two metal rods end to end on glass beakers so they touch, and bring a charged piece of plastic close to one end of the rods (Fig. 1). (Do not get the plastic so close that a spark jumps between the plastic and rod.) With the charged plastic close to the rods, separate the rods by moving one of the beakers without touching the rods. Remove the plastic and transfer some of its charge to a small piece of foil hanging by a thread from the crossbar of a ringstand. Move one rod and then the other close to the foil. How do you explain the results?

Now bring the rods into contact again and then bring them near the charged foil. How does the charged foil behave when it is near the rods?

Bring the charged plastic again close to one end of a single rod and touch the other end of the rod briefly with your finger. Remove the plastic and test for the presence of charge on the rod using the charged foil. Is the charge on the rod the same or opposite to the charge on the plastic?

The metal foil you have been using gives an indication of the presence and sign of a charge but is not good for measuring the quantity of charge. An electroscope is a better instrument than a piece of foil for measuring charge. Repeat the last part of the experiment, using an electroscope in place of both the rods and the foil.

Figure 1

IV-3. THE FORCE BETWEEN TWO CHARGED SPHERES

The force between electrically charged bodies depends on their separation and on the magnitude of their charges. The nature of the dependence can be measured in several ways. One simple method, which will be used in this experiment, measures the force on a charged body by balancing it against a known force—the force of gravity. We can suspend a small charged sphere with an insulating thread and bring another charged sphere close to it. From the deflection of the suspended sphere from the vertical, we can measure the electric force on it in terms of its weight.

Suspend a light, conducting ball A at the bottom of a "V" of very fine nylon thread so that it can swing in only one vertical plane (Fig. 1). Arrange a light to throw a shadow of the ball on a centimeter scale. Read the position on the scale of one edge of the shadow of the hanging ball. Charge the ball by induction and bring a like-charged ball B on an insulated support near it. Take readings of the two shadows on the scale for different positions of the balls as B is moved closer to A along a line that is in the plane of the ball's swing. Be sure to use the same side of each ball every time you read its position (P_1 and P_2 in Fig. 1).

Some charge may leak away slowly across the surface of the thread and the insulating support, thereby introducing an error. How can

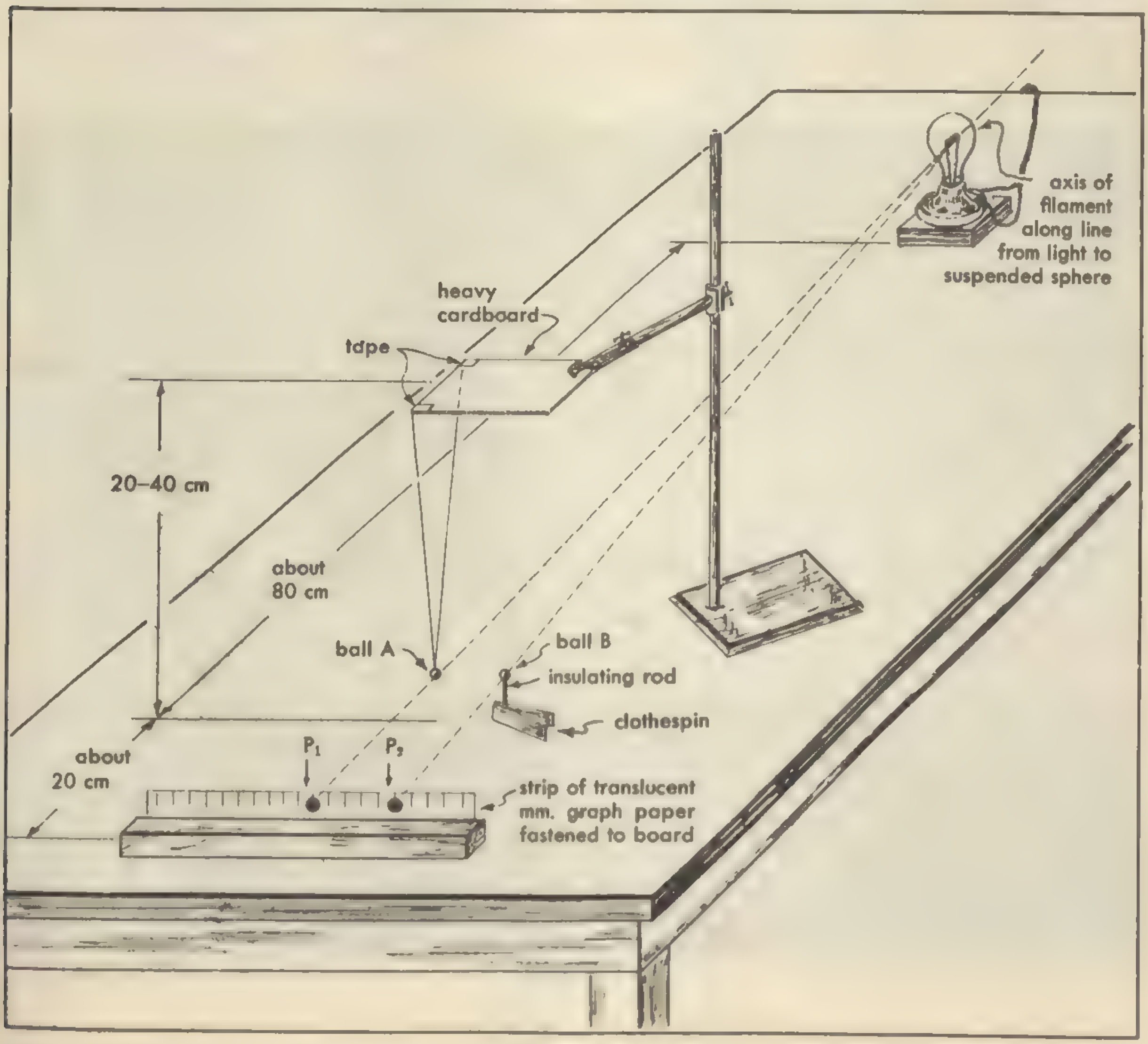


Figure 1

you test for leakage? When should you test for it, during the run or at the end?

When the suspended ball is at rest, the net force acting on it is zero. That is, the vector sum of the tension in the thread $\vec{T}$ and the weight of the ball $\vec{mg}$ is equal and opposite to the electric force $\vec{F}$. From Fig. 2 it can be seen that, for small angles, the ratio of the magnitude of the electric force to the magnitude of the weight $\frac{F}{mg}$ is equal to $\frac{d}{L}$, the ratio of the horizontal displacement of the suspended ball to the length of the suspension. Hence $F = \frac{mg}{L} d = (\text{constant}) \cdot d$.

Since we are not concerned here with particular units of force, we can measure the force in terms of d. Furthermore, the horizontal displacement d of the ball is proportional to the horizontal displacement D of its shadow on the scale. Similarly, the distance r between the two balls is proportional to the distance R between their shadows. We can, therefore, study the dependence of F on r by plotting D as a function of R.

Plot a graph of the force as a function of the separation of the two balls (note that the distance between the two shadows is proportional to the distance between the two balls). How is the force at a separation r related to the force at a separation of $\frac{1}{2}r$, $\frac{2}{3}r$? What kind of dependence does this suggest? Plot a graph to check it.

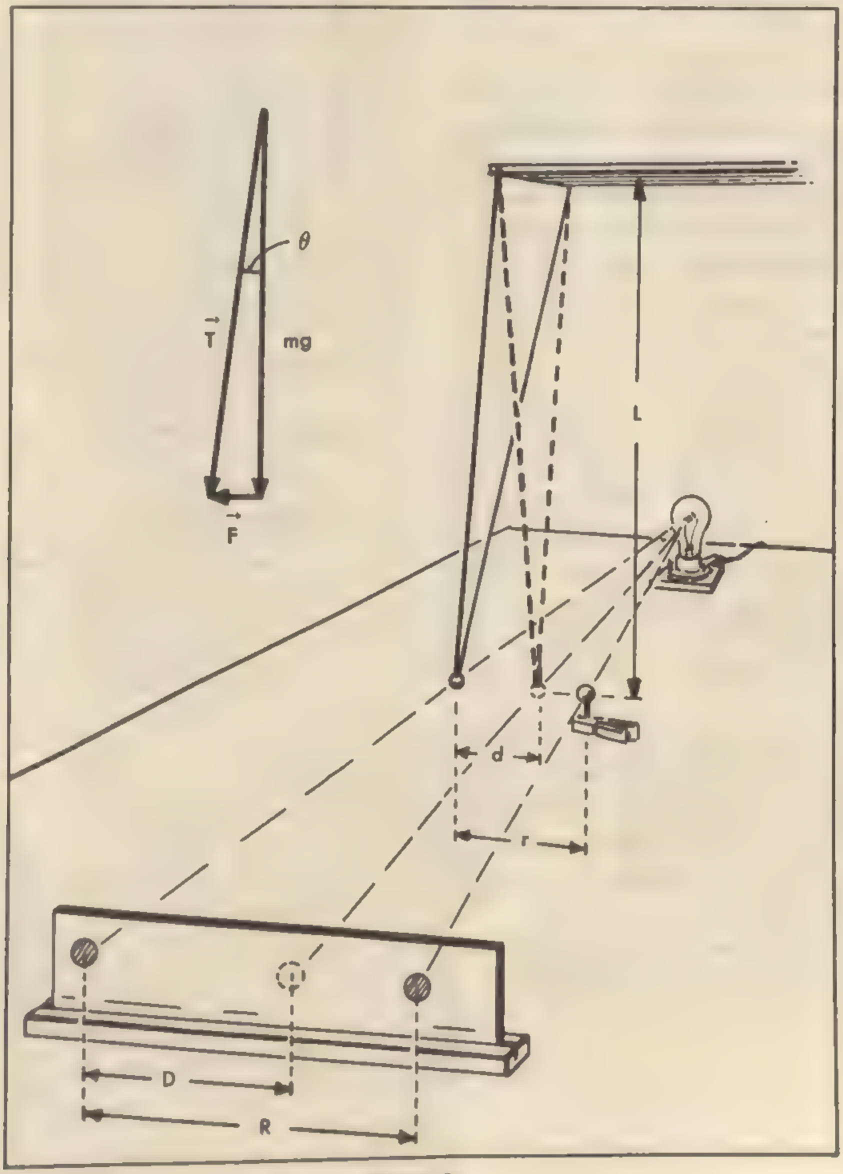


Figure 2

IV–4. THE ADDITION OF ELECTRIC FORCES

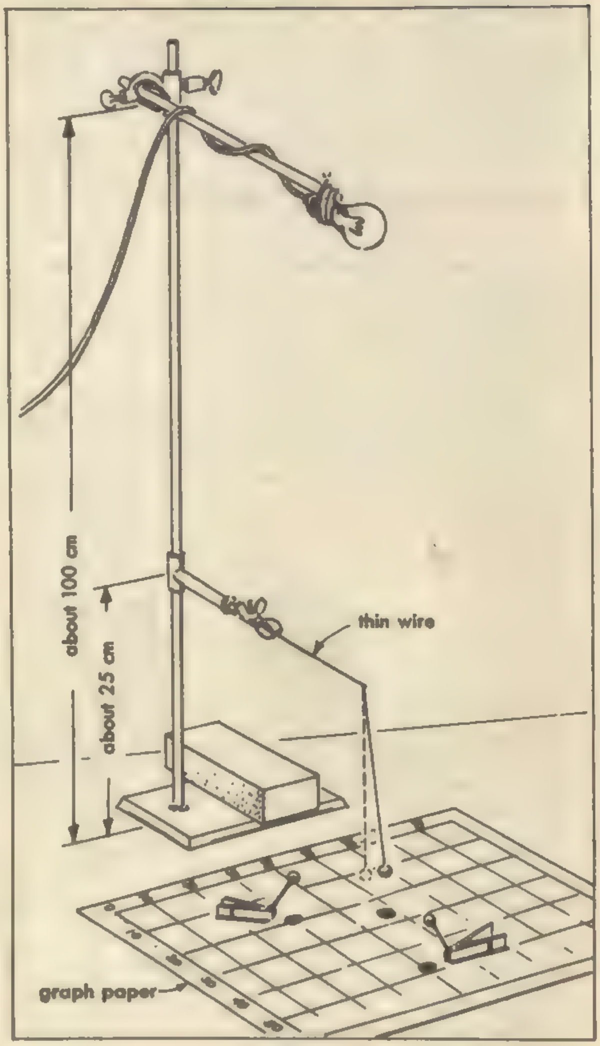


Figure 1

Suppose that two charged spheres, *A* and *B*, are brought near a third charged sphere *C*. How is the force exerted on *C* by *A* and *B* together related to the force on *C* due to *A* and *B* separately?

If we suspend sphere *C* by a single thread, we can measure both the direction and the magnitude of the force acting on it by measuring the direction and magnitude of *C*'s deflection. If we illuminate the spheres from above (Fig. 1), we can find the deflection of the suspended sphere and the positions of the other two spheres by locating their shadows on the graph paper taped to the table. We can then find out how electric forces add.

The supports of the movable spheres *A* and *B* (Fig. 1) are tilted to facilitate locating the center of their shadows. Mark the center of the shadow of the suspended sphere while it hangs vertically.

Charge the three spheres with like charges. Keeping sphere *A* far away, deflect the suspended sphere *C* several centimeters with sphere *B*. How far away should you move one charged sphere when you are measuring only the effect of the other? Record the coordinates of the shadows of spheres *B* and *C*. (Why shouldn't you mark the positions of the shadow of the suspended sphere *C* directly on the paper?) Now remove *B* and deflect *C* with sphere *A*, recording the positions of the shadows. Then, using both movable spheres, deflect *C* several centimeters. Before analyzing your data, find out if any appreciable charge has leaked away. If it has, repeat the experiment, working as rapidly as possible to minimize charge loss.

Using the inverse-square law, you can calculate, for any distance, the force with which spheres *A* and *B* act separately on *C*. From your measurements, calculate the force each of the spheres *A* and *B* exerts on *C* when they act together. How do they add?

If you have time, repeat the experiment using different positions of the movable spheres.

IV–5. *POTENTIAL DIFFERENCE*

Small potential differences, such as those supplied by batteries, may be measured by a sensitive electroscope called a "dosimeter." The movable element in the dosimeter is an extremely fine conducting fiber which is repelled from its conducting support when charged. The position of the fiber enlarged by magnifying lenses is read against a built-in scale. (Text, Section 27–6.)

To show that the dosimeter behaves like the electroscope used in Experiment IV–2, you can bring a piece of charged plastic near a lead connected to the sensitive fiber. What do you see as you look through the dosimeter while bringing a piece of charged plastic near the lead? (Note that the dosimeter fiber is off-scale to the right when it is either uncharged or slightly charged.)

Connect a string of batteries to the dosimeter as shown in Fig. 1, increasing the number of batteries until you can see the fiber near the right side of the scale. Be careful; the shock from a string of 45-volt batteries is dangerous! Observe the reading of the dosimeter. Now you can calibrate the dosimeter scale to measure potential difference in volts by adding more batteries to the string.

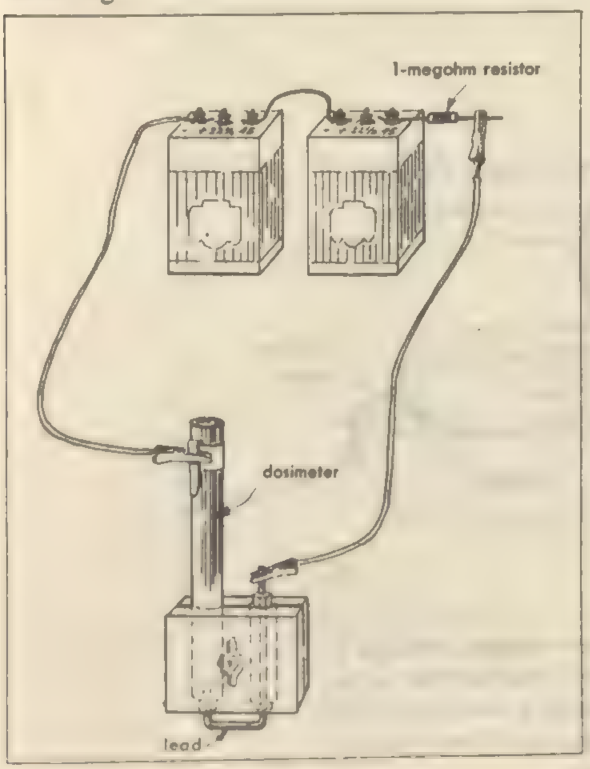


Figure 1

With the batteries, charge the dosimeter to some point near the middle of the scale. Remove the battery connection from the lead terminal and observe what happens when you bring a charged strip of plastic near the lead and when you bring your hand close to the lead without touching it. Now, with the battery connected, again bring the charged plastic and then your hand near the lead without touching it. What do you conclude?

Connect the dosimeter to a pair of parallel metal plates separated by insulators as shown in Fig. 2.

Charge the plates with the battery, and with the battery disconnected observe the rate of discharge of the dosimeter. Without touching the top plate, lift it to increase the plate spacing. Repeat this procedure with the plates connected to the battery. What do you conclude?

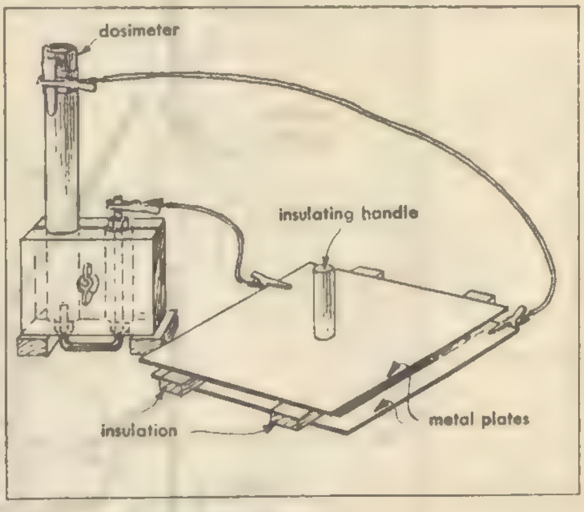


Figure 2

IV-6. *THE CHARGE CARRIED BY IONS IN SOLUTION*

When two copper electrodes are placed in a dilute solution of sulfuric acid and connected to a current source, bubbles of hydrogen gas form on the negative electrode (cathode) and rise to the surface. If we weigh the positive electrode (anode) before and after the current flows, we find that it loses mass, indicating that copper goes into solution. Evidently, ions of hydrogen and copper must be formed to carry the electric charges through the solution. In this experiment we shall find how much charge is carried by each hydrogen and copper ion.

The arrangement of the apparatus is shown in Fig. 1. Pour one liter of water from a graduated cylinder into the dish. While gently stirring the water, slowly add enough concentrated sulfuric acid to give a solution containing about 5 cm^3 of concentrated acid for every 100 cm^3 of water. Both concentrated and dilute sulfuric acid are very corrosive! Be careful!

Now fill the flask as completely as possible with solution by sucking on the suction tube. Clean and weigh the copper anode and put it in place as shown in Fig. 1. Connect the electrodes, an ammeter, and a variable resistor to a source of current (Fig. 2). Run about five amperes through the solution until the level of the solution in the flask is the same as the level in the dish, carefully noting the current and the time of starting and stopping the current flow. Be sure to keep the

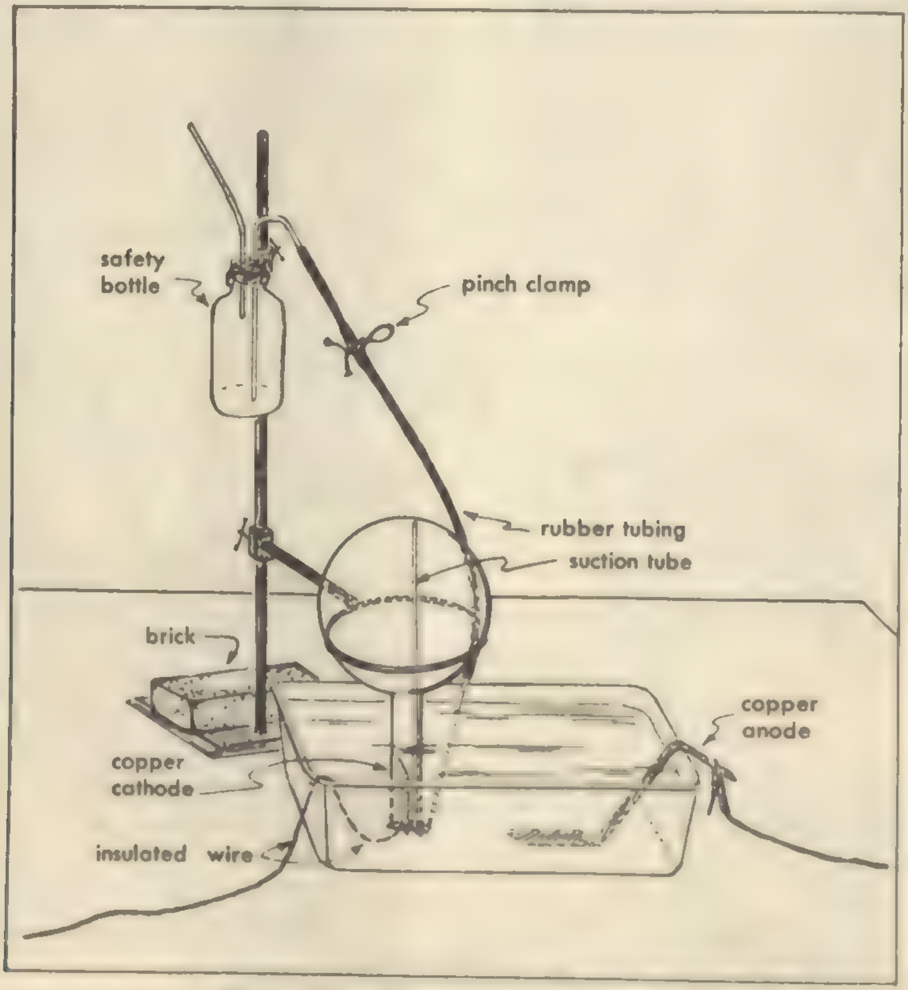


Figure 1. **Insert the copper cathode attached to an insulated wire into the flask. Also insert the suction tube, which should be long enough to reach the bottom of the flask. Invert the flask and mount it with its mouth close to the bottom of the dish.**

current constant throughout the run. How many elementary charges passed through the solution?

Rinse and dry the copper anode and find the decrease in mass. How many moles of copper ions were formed? How many elementary charges were carried by each ion? What is the most important assumption you had to make in answering this question?

Mark the flask at the water level, then remove and rinse it and, from the volume of the gas, find the number of moles of hydrogen gas produced. What charge was carried by each hydrogen ion?

How would you use the apparatus to show that the mass m of material deposited or dissolved by a flow of charge q is given by the equation

$$m = \alpha q,$$

where α is a constant? How does the value of α for copper compare with the value for hydrogen?

How could you show that for each substance α is the mass per ion divided by a small whole number? What is the significance of this whole number?

Does copper leaving the anode deposit on the cathode? How would this affect your calculated results?

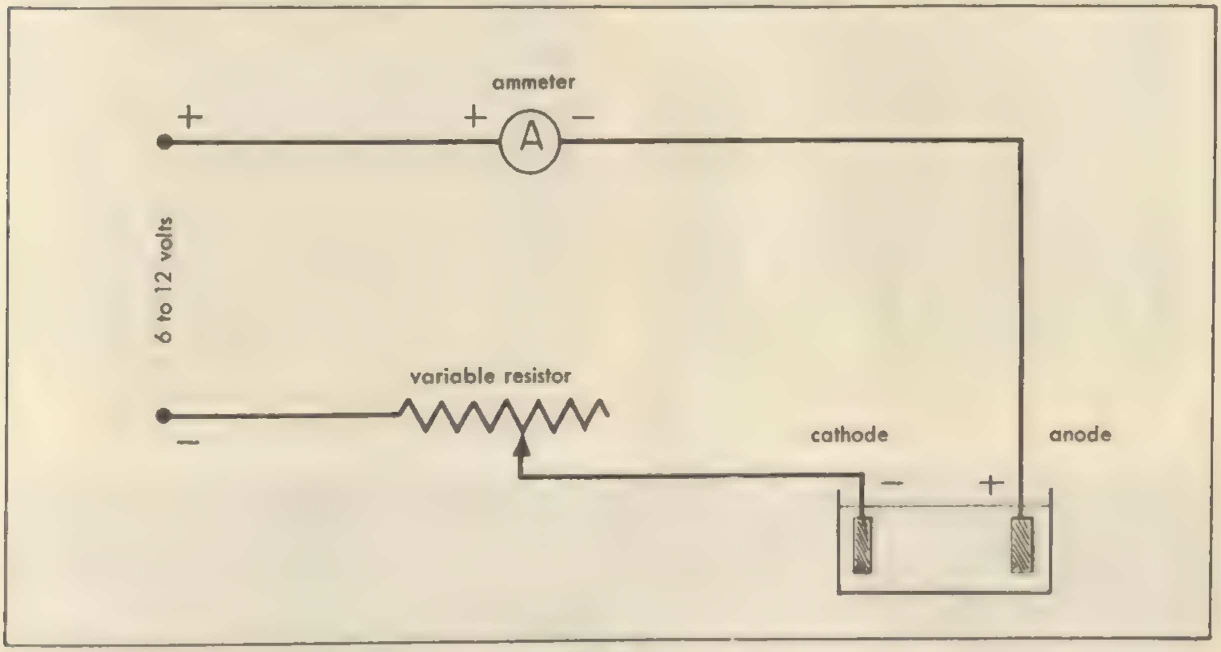


Figure 2

IV–7. *THE MAGNETIC FIELD OF A CURRENT*

Place a magnetic compass over a long piece of wire and momentarily touch the two ends of the wire to the terminals of a dry cell. The compass needle moves. Apparently the current in the wire creates a magnetic field which deflects the compass. How can we find the dependence of the direction and magnitude of a magnetic field on the current that produces it? A compass will indicate the direction since it aligns itself in the field and the magnitude of the field can be measured by comparing it with the constant field of the earth.

First investigate the direction of the magnetic field in the center of a coil of wire in the following way: Wind the wire into a coil of several turns on a frame as shown in Fig. 1. Place the compass in the center of the coil and note the direction of the needle when there is no electric current in the coil. Now connect the coil through a flashlight bulb to a dry cell as shown in Fig. 2 and note the direction of the needle. The bulb keeps the current small.

Connect the coil directly to the terminals of the dry cell and observe the direction of the needle. (Do not leave the cell connected longer than necessary, because the large current flowing through the wire runs the cells down rapidly.) Turn the coil through a horizontal angle of about 30° and again note the direction of the field when a large current flows through the coil. What do you conclude about the direction of the field in the center of the coil due to the current?

Reverse the direction of the current and repeat the experiment. What is the effect of reversing the current on the direction of the field?

With only one turn of the long wire on the frame, align the frame with respect to the earth's magnetic field so the compass needle, placed at the center of the coil, lies in the plane of the coil. Again connect the ends of the wire to the dry cell through the flashlight bulb. The magnetic field produced by the current will be about the same order of magnitude at the center of the coil as the horizontal component of the earth's field. Be sure that the wires from the coil to the cell are kept away from the loop so the magnetic field

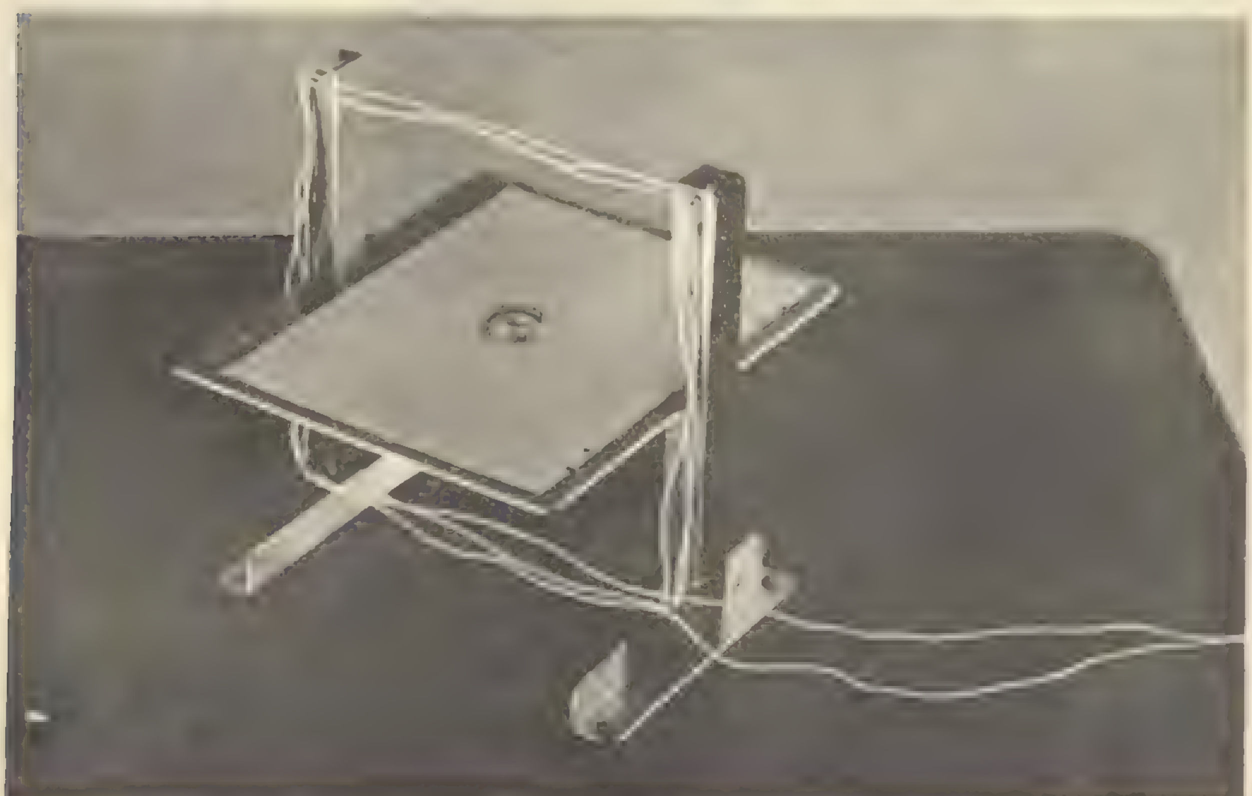


Figure 1

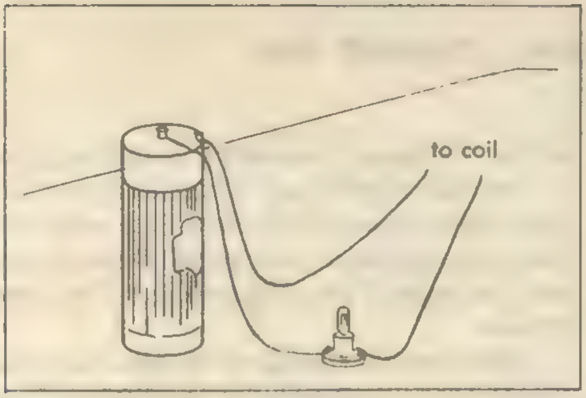


Figure 2

from the current flowing in them will not contribute measurably to the field at the center of the coil. Measure the angular deflection of the compass needle. Reverse the direction of the current and again read the needle deflection.

Draw a vector diagram to find the strength of the magnetic field in terms of the earth's field.

Double the current flowing around the loop by adding another turn of wire to the coil and measure the compass deflection for both directions of current flow. Keep increasing the current in steps by adding turns of wire. When you have finished taking data, determine the field strength for each case by means of vector diagrams or trigonometry. What do you conclude about the magnitude of the magnetic field as a function of the current?

What will happen if you wind the coil with some turns going in one direction and others going in the opposite direction? What do you predict will be the magnitude of the resulting field? Measure the field to check your prediction.

Could you have measured the field resulting from the current if, initially, the needle was not parallel to the plane of the coil? Will the strength of the magnetic field of the compass needle influence the results of this experiment?

An alternate method of varying the current flowing around the loop is to vary the resistance of the circuit by means of a variable resistor connected with the coil. The circuit connections are shown in Fig. 3. If you have time, use this method. Are the field strengths measured for different ammeter readings consistent with the conclusions you have reached in the earlier part of the experiment about the field strength as a function of current?

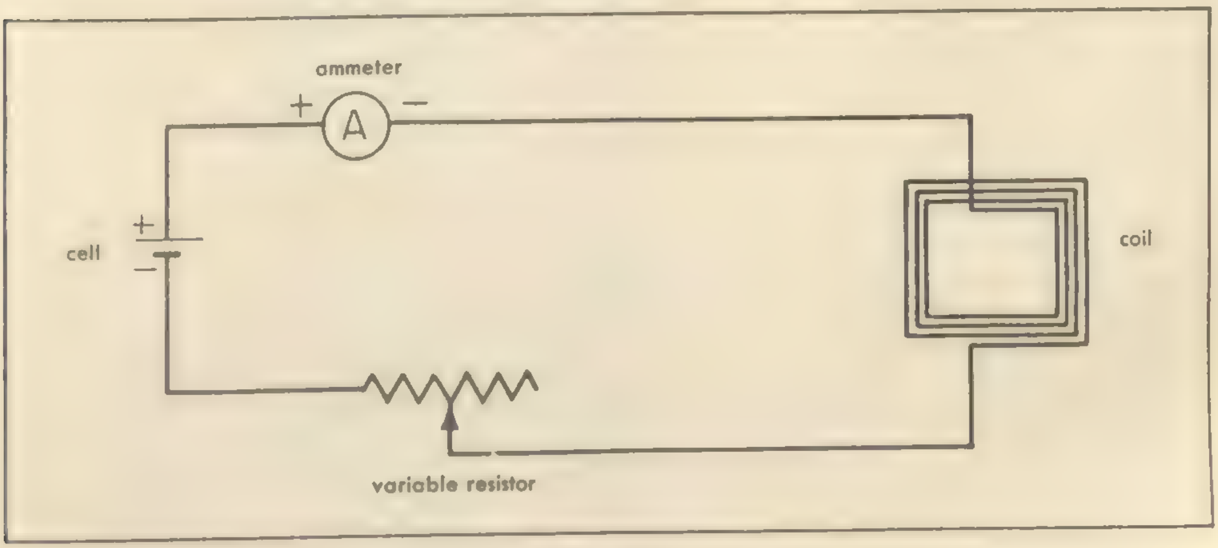


Figure 3

IV–8. *THE MAGNETIC FIELD NEAR A LONG, STRAIGHT WIRE*

In the last experiment we used a compass to determine the magnetic field in the center of a loop of wire. Now we shall use the same method to find the field about a long, straight wire and its dependence on the distance from the wire.

Support a long, straight wire next to a sheet of graph paper which is aligned parallel to the horizontal component of the earth's field as shown in Fig. 1. The wire is held in position next to the table's edge by a piece of tape, and the graph paper is taped to the table top. Be sure there are no iron objects within 50 cm of the sheet of graph paper on which you will move the compass around. Except for the straight vertical section, all parts of the long wire should be at least 50 cm from the paper.

Allow a constant current of about 5 amperes to flow through the wire and determine the direction of the field around it. To find the magnitude of the field, measure the deflection of the compass needle. Do this for different distances out to about 20 cm, moving the compass in steps along a line parallel to the horizontal component of the earth's field. If you try to measure the field at a distance comparable to the length of the compass needle, you will have large errors since different parts of the needle are subject to widely varying forces. It is therefore best to start with the center of the compass about 5 cm from the wire.

How does the strength of the field due to the current vary as a function of the distance from the wire? How do you arrive at this conclusion?

Why was it necessary to keep the rest of the wire and iron objects far away from the compass?

How would the results have differed if the vertical wire had been only 20 cm long?

How would the accuracy of your results have been affected if you had used a current a hundred times larger? A hundred times smaller?

Set up two parallel vertical wires about 20 cm apart in a plane parallel to the direction of the earth's field. Find how the magnetic field varies along a line between them (a) when the currents in the wires are in opposite directions; (b) when the two currents are in the same direction. How do you explain your results?

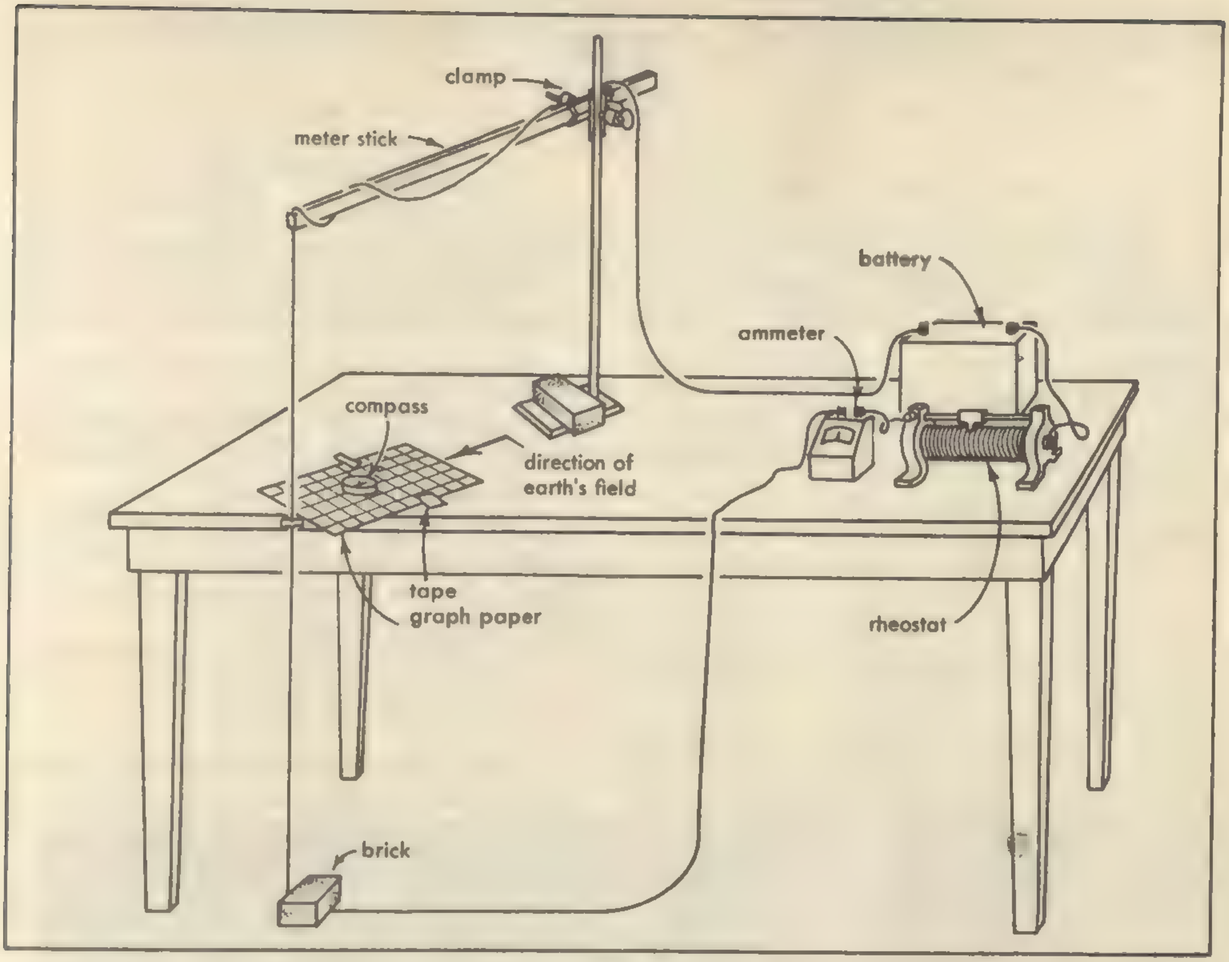

clamp
meter stick
battery
ammeter
compass
direction of
earth's field
tape
graph paper
rheostat
brick

Figure 1

IV-9. THE MEASUREMENT OF A MAGNETIC FIELD IN FUNDAMENTAL UNITS

In previous experiments we measured magnetic field strength in terms of the horizontal component of the earth's magnetic field. In this experiment we shall measure magnetic fields in more fundamental units, using the fact that a magnetic field exerts a force on a current-carrying wire. If we measure the force F in newtons, the current I in amperes, and the length of the wire L in meters, the strength of the field B in $\frac{\text{newtons}}{\text{ampere-meter}}$ is given by

$$B = \frac{F}{IL}$$

provided the wire is perpendicular to the direction of the field.

Fig. 1 shows a sensitive balance that we can use to measure the force on a short length of current-carrying wire in a magnetic field. If the balance is so aligned that the end of the U-shaped metal loop (A in Fig. 1) is perpendicular to the field while the sides are parallel to it, only the end will be subject to a force from the field. We can measure the force on the end of the loop by balancing it with a known weight hung from the other end of the balance.

In this experiment we will determine the magnitude of the magnetic field in the center of a long coil (a solenoid) of current-carrying wire. Connect the loop, coil, variable resistors, and ammeters to a source of current as shown in Fig. 2. Be sure both the pointed tips of the loop and the tops of the supporting nails are clean and shiny so that good electrical contact will be made.

With no current flowing in the apparatus, move the end of the loop into the center of the coil (Fig. 3). Level the loop by adjusting the position of the nut. Now, with a current of about 4 amperes, establish a magnetic field in the center of the coil. You can then measure this field by passing a current of about 1 ampere through the loop and finding the force needed to balance it. Roughly balance the loop with a short piece of string and then level it exactly by adjusting the current through it. (If the current in the loop fluctuates wildly when the balance is swinging, the contacts are corroded or rough.)

Find the weight of string needed for balance with other values of current in the loop. (The current in the loop should not exceed 5 amperes or the contacts will corrode.) What is the strength of the field in the center of the coil in $\frac{\text{newtons}}{\text{ampere-meter}}$? What is the field strength in newton-seconds per elementary charge per meter? (1 ampere = 6.25×10^{18} elementary charges/second.)

Measure the field in the coil resulting from several other values of current in the coil. (Five amperes is the maximum current the coil can carry without overheating.)

Do your measurements show that the field inside the coil is proportional to the current flowing through it?

Could you use this apparatus to measure the field near a small permanent magnet? Can you use it to measure the field of the earth directly?

Why don't you use iron for the loop of the balance?

Note: Save your data. You will want it in the next experiment.

Figure 1

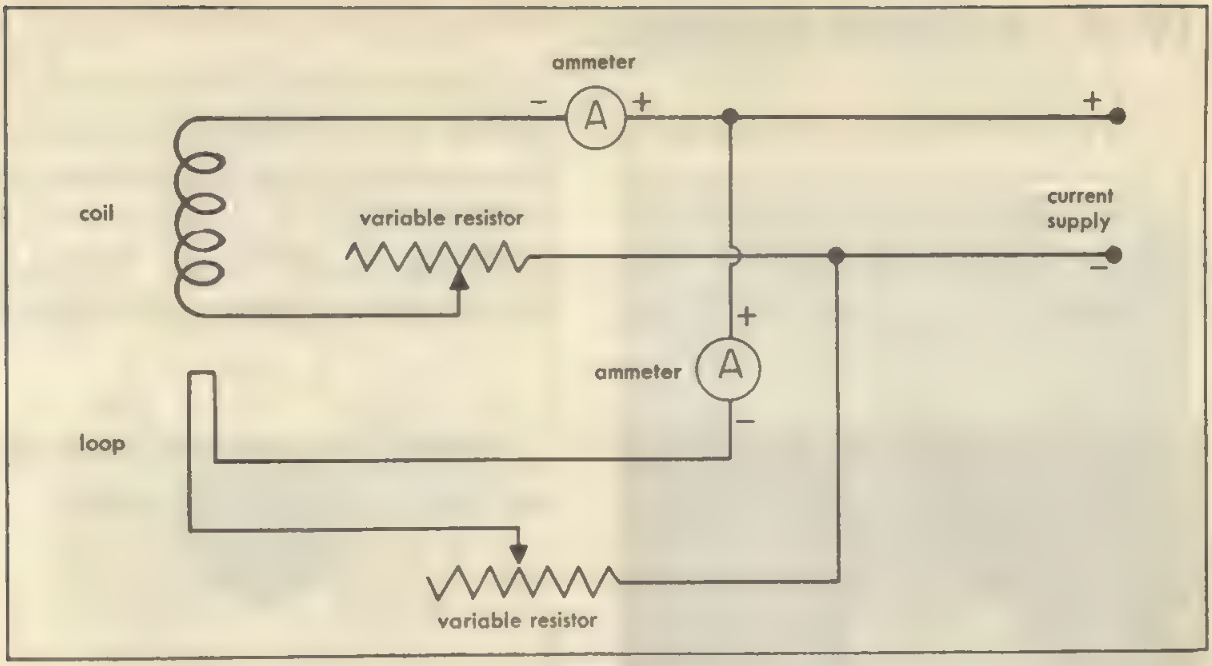


Figure 2

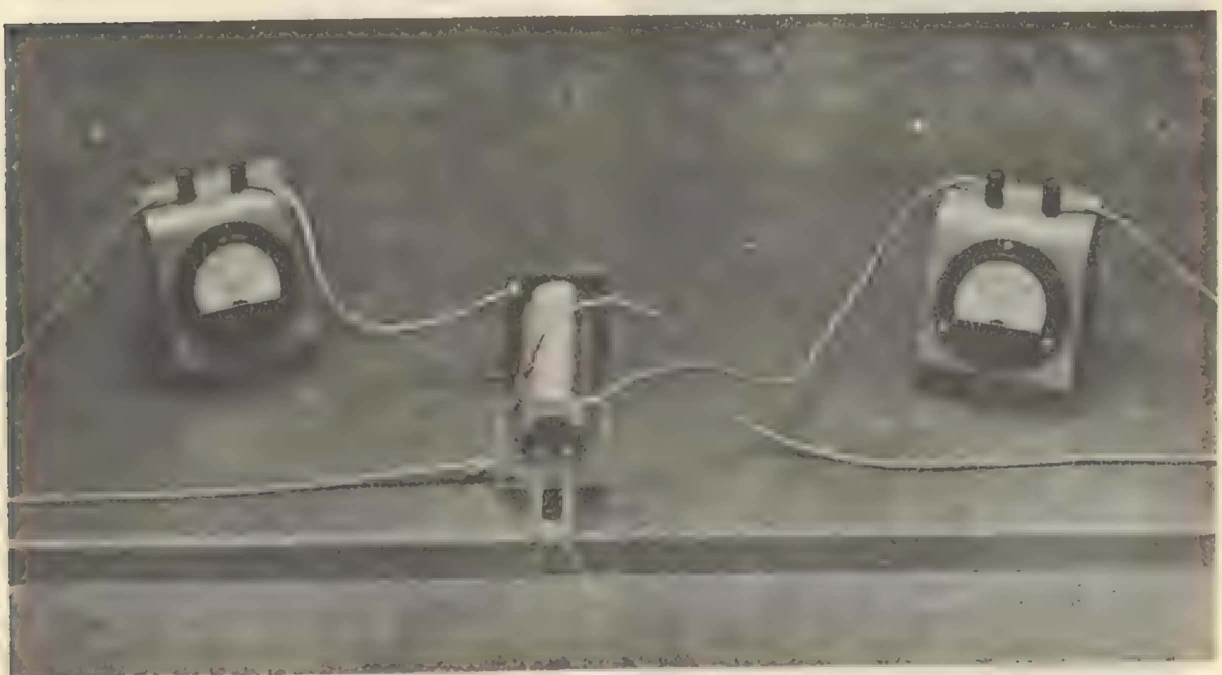


Figure 3

IV-10. THE MASS OF THE ELECTRON

An electron, initially at rest, accelerates in an electric field and acquires kinetic energy equal to the product of its charge and the potential difference through which it moves; $\frac{mv^2}{2} = qV$. If the electron with velocity v then moves through a uniform magnetic field perpendicular to its direction of motion, the field exerts a centripetal force perpendicular to the electron's motion and the direction of the field. This force depends on the magnetic field strength B, the charge of the electron, and its speed; $F = Bqv$. The electron will follow a circular path of radius R given by

$$F = \frac{mv^2}{R}.$$

Equating the two expressions for the magnetic force, $F = Bqv$ and $F = \frac{mv^2}{R}$, gives

$$v = \frac{BqR}{m}$$

or

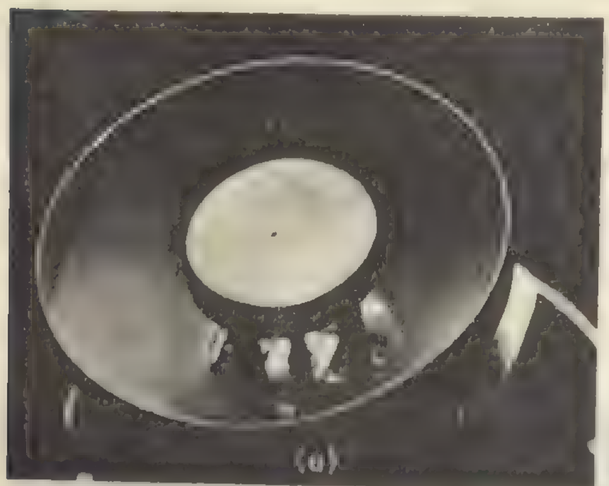
$$v^2 = \frac{B^2q^2R^2}{m^2}.$$

Substituting this expression for v^2 in the equation $\frac{mv^2}{2} = qV$ gives

$$m = \frac{B^2qR^2}{2V}.$$

Instead of using a tube like that described in the text for accelerating and deflecting electrons, we shall use a common, commercial vacuum tube used in tuning a radio. Fig 1 shows the construction of this tube. The electrons emitted by the cathode are accelerated by the potential difference between the cathode and the anode. They move radially outward in a fanlike beam, reaching nearly their maximum velocity by the time they emerge from beneath the black metal cap covering the center of the tube. Their speed is approximately constant over the remainder of their path to the anode.

The anode is coated with a fluorescent material which emits light when electrons strike it. Since it is conical in shape, we can see the path the electrons follow as they move outward from the cathode; when we look straight down from above, the conical anode slices the electron beam diagonally, showing the position of the electrons at different distances from the cathode. Two deflecting electrodes are connected to the cathode and, with no magnetic field present, they repel electrons moving toward them from the cathode



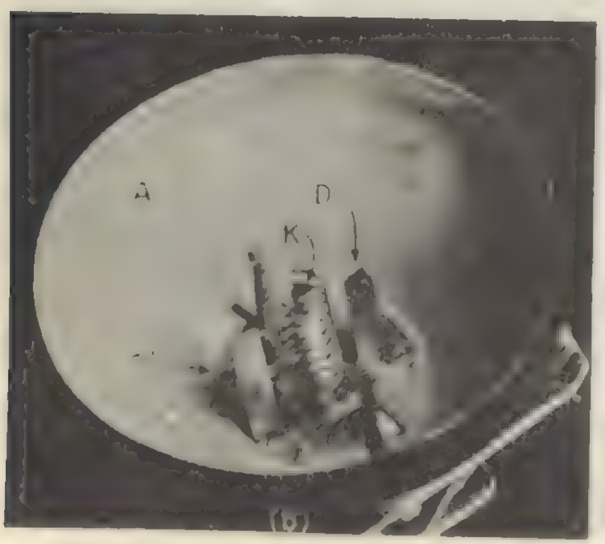


Figure 1 (a). An electron tube or tuning eye with glass envelope removed.

Figure 1 (b). The metal center cap shown in (a) has been cut away from its wire supports and removed, revealing the important parts of the tube structure. K is the electron-emitting cathode. D and D′ are the deflecting electrodes that form the shadow and A is the anode coated with a fluorescent material.

and form a wedge-shaped shadow behind them (Fig. 2).

When the tube is in a uniform magnetic field parallel to the cathode, the electrons are deflected in an almost circular path as shown by the curvature of the edge of the shadow (Fig. 3).

You will put a uniform magnetic field on the tube by inserting the tube into the center of a

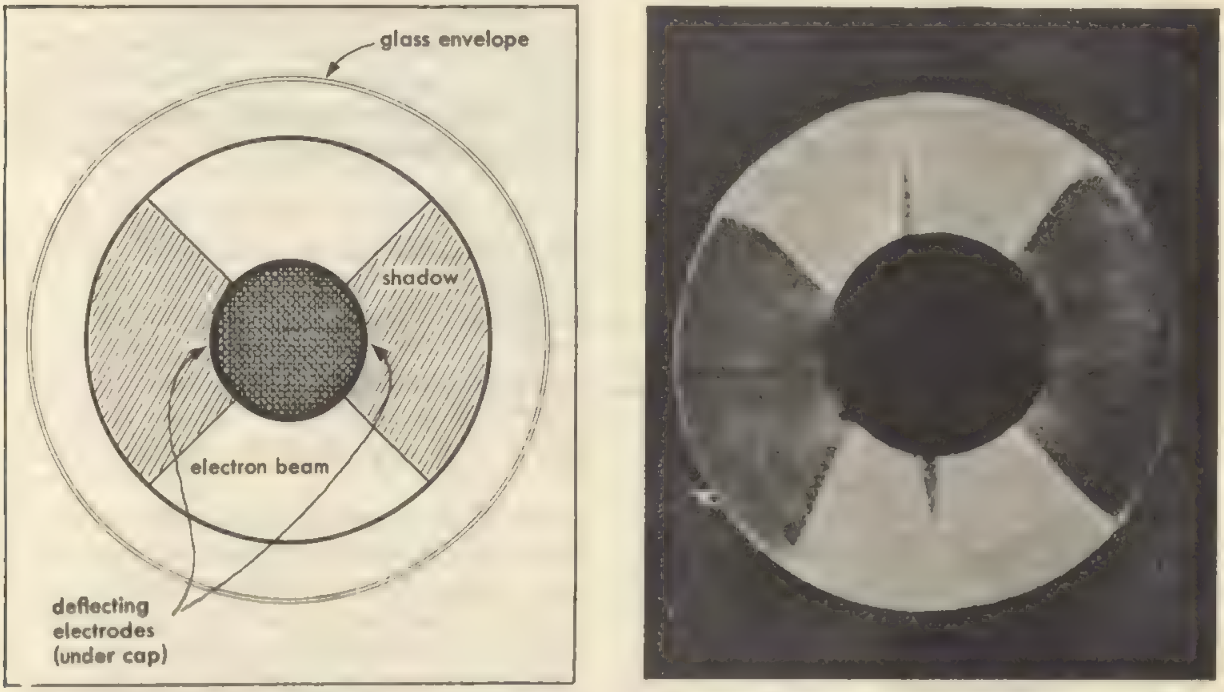


Figure 2. The drawing (left) shows the shadow and the radial beam we expect to see when there is no magnetic field in the tube. On the right is a picture of the tube in actual operation with no magnetic field applied; the two narrow shadows are caused by the wires supporting the center cap.

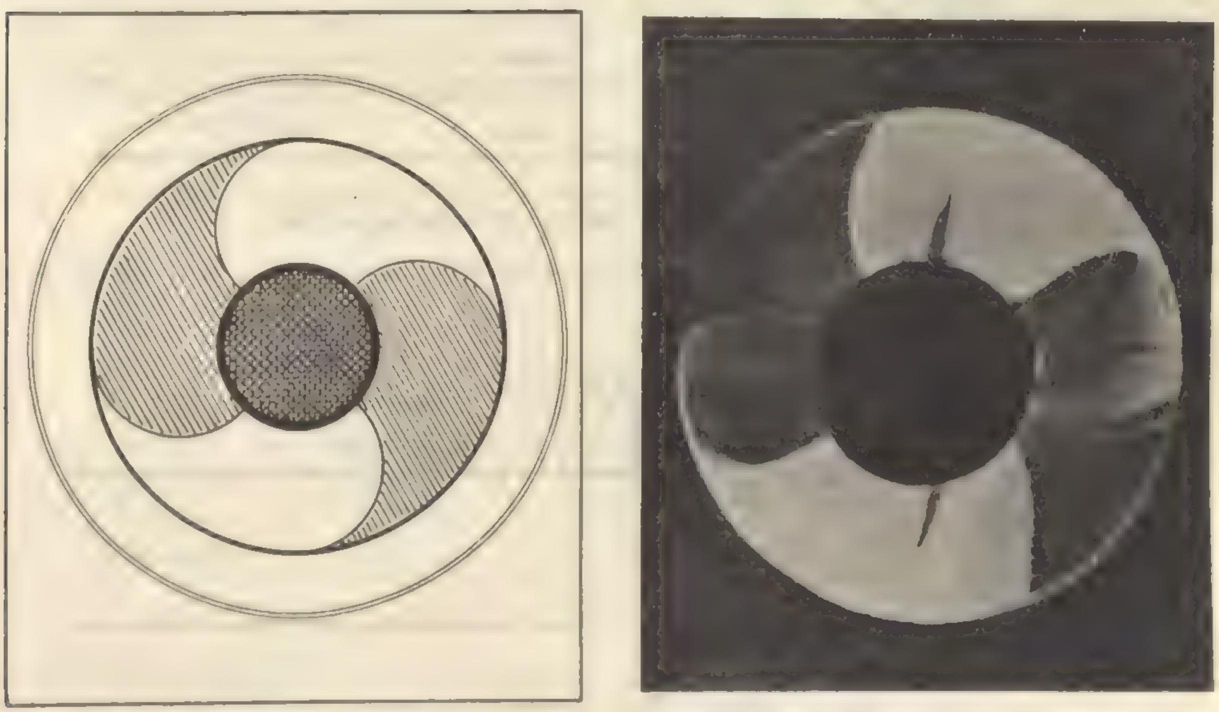


Figure 3. The shape we expect the beam to have when the tube is in a magnetic field is shown on the left. The photograph on the right shows the actual appearance of the beam when it is deflected by a magnetic field.

long coil. Connect the coil and tube as shown in Fig. 4. Set the anode potential to between 90 and 250 volts and then vary the current flowing through the coil until the curvature of the edge of the shadow is estimated to be the same as some small round object whose radius can be easily measured. A dime, a piece of wooden dowel, or a pencil will do.

Make measurements for several different anode potentials. (1 volt = 1.6×10^{-19} joule per elementary charge.) Also, use several different magnetic fields. (How do you know the magnetic field?) Calculate mass of the electron.

Would it be possible to use the earth's magnetic field to deflect the beam? How large a tube would you need? Assuming the earth had no magnetic field, would it be practical to determine the mass of an electron by accelerating it horizontally through a known potential difference and subsequently observing its deflection in the earth's gravitational field?

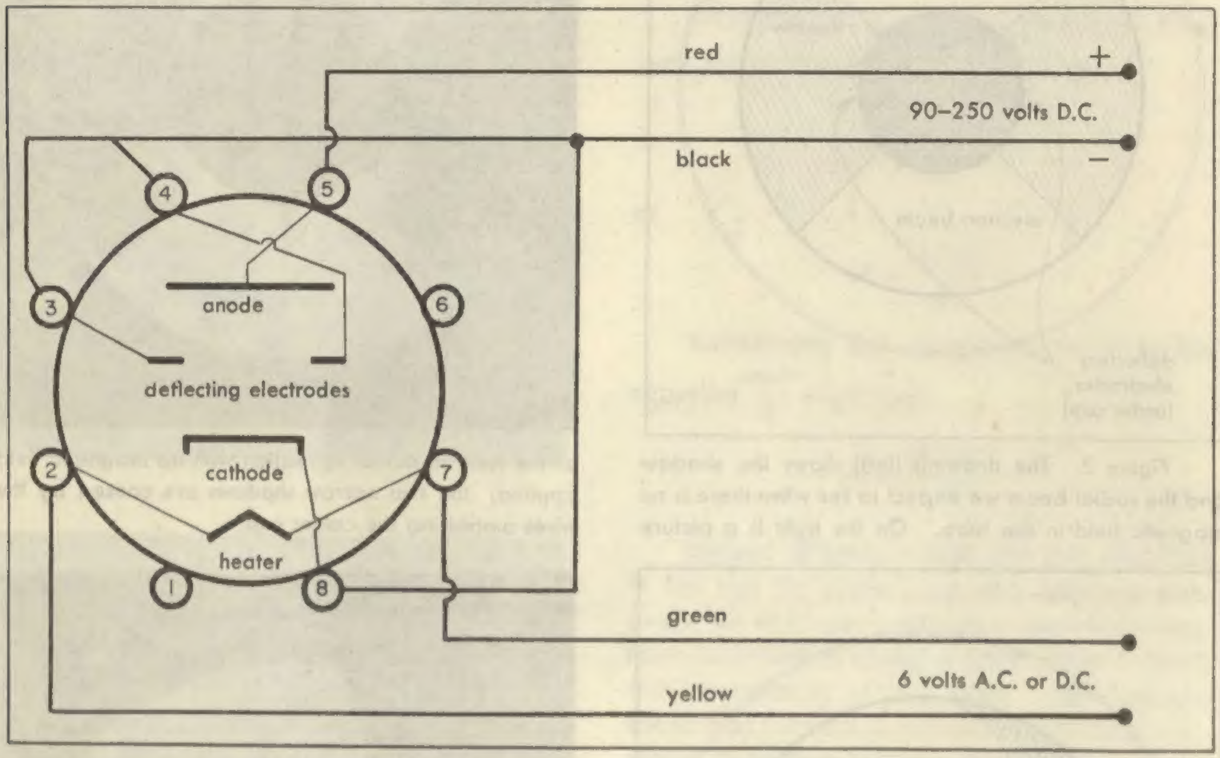


Figure 4 (a). **Circuit connections for type 6AF6 electron ray tube.**

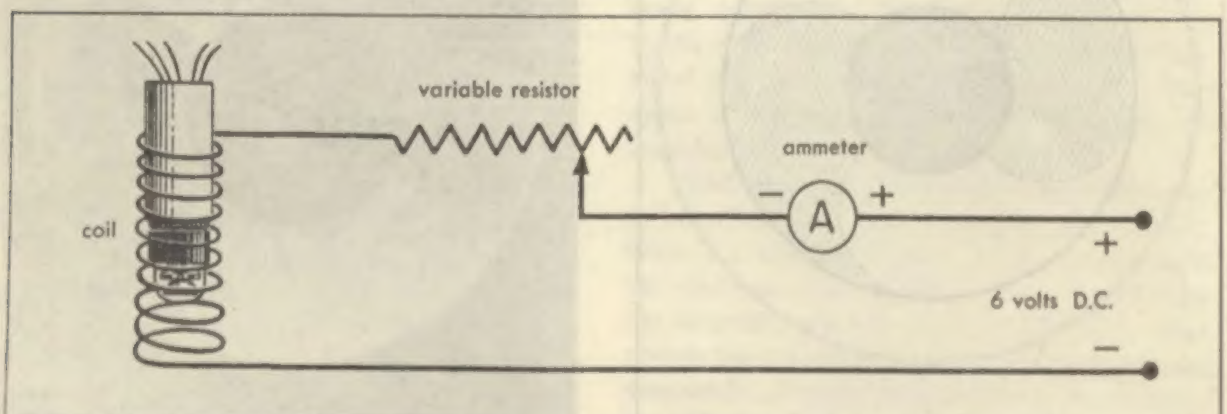


Figure 4 (b). **Circuit for coil.**

IV-11. *RANDOMNESS IN RADIOACTIVE DECAY*

Radioactive elements emit particles which can be counted by a Geiger counter. Each click of the counter represents the decay of a single atomic nucleus. What can we find out about the rate at which a radioactive sample decays?

Place the probe of a Geiger counter far enough from a radioactive sample so the clicks come slowly enough to count easily. Once the probe and counter are in position, do not move them. Make a few 10-sec practice counts and then count the clicks continuously for twenty minutes, recording the number counted during each 10-sec interval. You will undoubtedly find that the number of counts per interval will vary.

Make a bar graph of your results, plotting the number of intervals N, in which k clicks are heard, as a function of k. From this graph, what do you estimate the average counting rate to be?

Now add the count obtained in the second 10-sec interval to the count obtained in the first, and divide by two to find the average counting rate over a 20-sec interval. Then add the count found in the third interval to the sum of the counts in the first two intervals and divide by three to find the average rate over a 30-sec interval. Continue this process, interval by interval, until you arrive at the average counting rate over a period of 15 to 20 minutes. How does the average rate over the whole period compare with the estimate you made from the bar graph? Plot the average counting rates obtained in this way as a function of the total count used for each successive calculation.

How does the accuracy of the measurement of the counting rate appear to depend on the total number of counts used in the calculation? What counting rate would you expect to find if you counted clicks for two hours? Would this increase your accuracy?

Since only a small fraction of the particles emitted by the sample hit the counter, the counting rate you obtained is much less than the rate of decay of the sample. How would you calculate the average number of atoms that disintegrate in each second (the rate of decay of the sample)?

Can you determine the half-life of the sample from your measurements?

You can do this experiment using a cloud chamber and a weak radioactive sample on a needle tip inside the chamber. How would the counting rate be related to the rate of decay?

IV-12. SIMULATED NUCLEAR COLLISIONS

Nuclear collisions are often studied in photographic emulsions and in cloud chambers. In these instruments, charged particles moving at high speed ionize atoms along their paths and leave visible tracks. The energy to ionize the atoms comes from the kinetic energy of the charged particles which therefore slow down. The distance a particle travels in the chamber before it comes to rest is called its range. The range depends on the particle's kinetic energy as it enters the chamber. By shooting particles of known energy into the chamber, we can establish the relation between range and energy. We can then use this relation to find the energies of particles by observing their ranges. In this way we can find the energies of particles emerging from a nucleus as the result of a collision. If the masses of the particles are known, we can then find their momenta.

There is strong evidence that momentum is conserved in nuclear collisions. When we observe a collision in which momentum appears not to be conserved, we conclude that at least one uncharged particle, which left no track, carried the missing momentum.

In this experiment you will study a situation analogous to a nuclear collision; the particles will be nickels and the emulsion or cloud chamber will be a sheet of paper which the nickels slide across until brought to rest by friction. The distance a nickel slides across the paper (its range) depends on its kinetic energy. To find the range-energy relation for a nickel, we can launch it down an incline, giving it different energies by starting it from different heights (Fig. 1). We then measure how far the nickel slides before coming to rest for each energy we give it. From the mass and the range-energy relation, we can find the velocity and momentum of the nickel when it comes out of a collision.

Before simulating a nuclear collision, we must find the range-energy relation for nickels. Select three nickels that slide easily down the ramp and have nearly the same range when sliding with the same face down. Find the distances these nickels slide on the paper for different release heights. Make several runs at each height and record the average range for each height. How is the kinetic energy at the bottom of the incline related to the release height? (Friction on the steep incline may be ignored.) A graph of the kinetic energy as a function of the range is the range-energy relation.

We are now ready to simulate a nuclear collision by placing a nickel (the nucleus to be hit) on the paper, and sliding another nickel down the incline, giving it a known kinetic energy. (The incline corresponds to an accelerator giving an atomic particle a known kinetic energy.) The target nickel should be about 10 cm from the bottom of the incline to keep the incident nickel from bouncing over it.

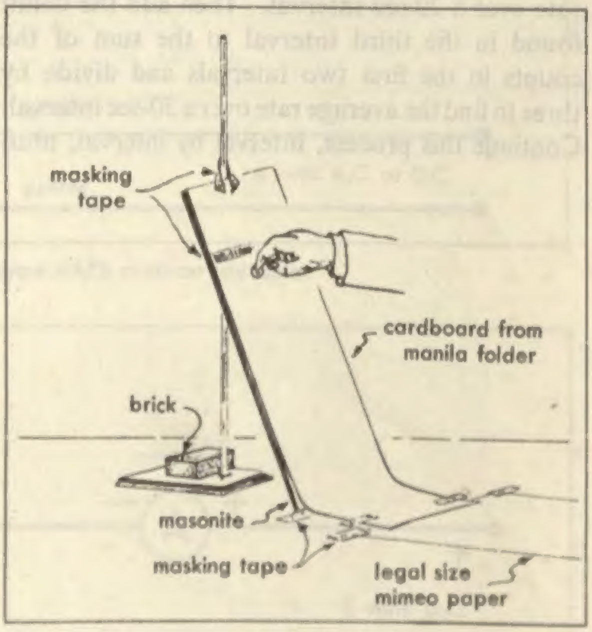


Figure 1

The next part of the experiment should be done by one partner while the others are not present. Slide a nickel down the incline at the target nickel. Record the release height on the incline, the final position of the incident nickel, and the initial position of the target nickel. Secretly record the final position of the target nickel by coordinate measurements along two edges of the paper. The other laboratory partners now find the momentum and final position of the target which corresponds to an uncharged atomic particle leaving no visible track. To find the position of the incident nickel at the instant of collision, see Fig. 2.

What fundamental law have you assumed in finding the unknown momentum? What fraction of the kinetic energy of the incident nickel is lost in this collision?

Repeat the experiment using two nickels placed next to each other as the target. Find the "unknown" momentum and final position of one of the target nickels.

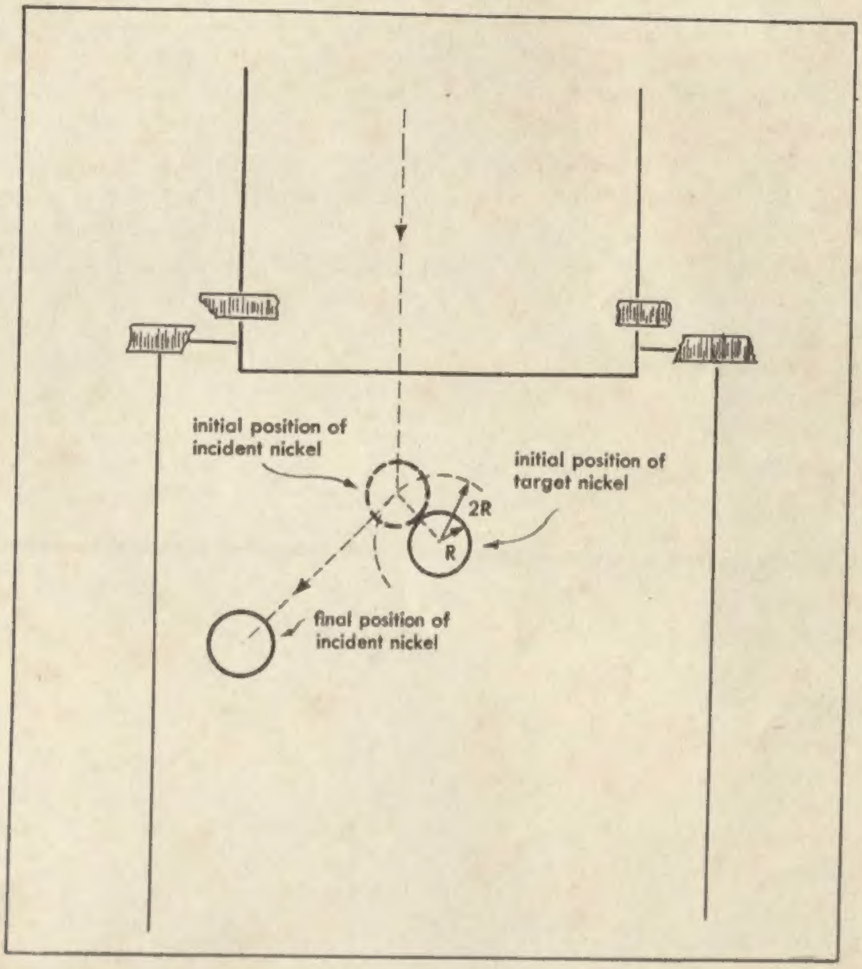


Figure 2